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Theme Issue: Evolution and Darwin

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About Our Cover

The cover photograph shows a tulip-tree beauty (*Epimecis hortaria*) doing what it and many of its fellow moths do so well – getting "lost" amid their background. This particular moth was found hiding on the bark of its namesake, a tulip poplar (*Liriodendron tulipifera*). The tulip-tree beauty's coloration pattern, a product of chance mutations and natural selection, allows it to blend in with its background and minimize detection by predators. This strategy is especially advantageous for the females, which prefer to find a safe place and wait patiently while releasing pheromones to alert males of their presence and their willingness to create the next generation.

Although moths have been around for approximately 200 million years, scientists are not quite sure what to do with them taxonomically. They are currently grouped with the butterflies in the order Lepidoptera. However, unlike their fellow lepidopterans, the moths are not considered a natural group – that is, one whose members arose from a common ancestor.

The photo was taken using a tripod-mounted Nikon D750 with a 60 mm MicroNikor lens and a remote shutter release. The photographer is Bob Ford of Frederick Community College, Frederick, Maryland.

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GUEST COMMENTARY

Glenn Branch

All Aboard the Evolution Bus!

Evolution is the latest stop on the itinerary of the Magic School Bus. Speaking to *PBS NewsHour* about her new book *The Magic School Bus Explores Human Evolution*, Joanna Cole affirmed the centrality of evolution in biology, borrowing Theodosius Dobzhansky's famous dictum "Nothing in biology makes sense except in the light of evolution." As Ms. Frizzle would have cheered, "Excellent observation, Joanna!"

Ms. Frizzle, of course, is the enthusiastic if eccentric elementary school science teacher who is the star of the Magic School Bus series, taking her students – even the timorous Arnold Perlstein – on magical field trips to increase their understanding and appreciation of topics throughout science. Whether Ms. Frizzle is a member of NABT or not is unclear, but she certainly is on board with NABT's important, and recently updated, statement on the teaching of evolution.

Why is NABT's statement on the teaching of evolution so important? In the first place, the statement demonstrates that NABT is aligned with the consensus of the scientific community – a consensus that is both genuine and substantial. According to a 2014 survey conducted by the Pew Research Center, for example, 98% of scientists – and a whopping 99% of active research scientists – accept evolution.

Reflecting the scientific consensus, the nation's leading scientific organizations, including the American Association for the Advancement of Science and the National Academy of Sciences, have issued statements affirming the scientific credibility of evolution (collected in *Voices for Evolution*, a publication of the National Center for Science Education). It is obviously in order for NABT to follow their lead.

So NABT's statement is important as a signal that NABT – the professional society that represents the interests, establishes the standards, and expresses the values of life science educators in the United States – is wholeheartedly committed to the central role of evolution in biology education, as part of its mission to provide the best possible biology and life science education for all students.

Such a strong signal is vital to teachers who are embroiled in a controversy over evolution education – a reminder that NABT is ready, willing, and able to support teachers under pressure to compromise their teaching of evolution. Such pressure is sadly common: over one in five public high school biology teachers reported experiencing it, according to a national survey conducted in 2007 by Michael B. Berkman and Eric Plutzer.

NABT was not founded until 1938, so it could not aid John T. Scopes in 1925. But it provided valuable support to such teachers as Susan Epperson, who successfully challenged Arkansas's ban on the teaching of evolution; Donald W. Aguillard, who successfully opposed Louisiana's law requiring the teaching of creation science; and the teachers in Dover, Pennsylvania, who successfully resisted a local policy requiring the teaching of intelligent design.

Teachers under pressure to compromise their teaching of evolution are not the only audience addressed by NABT's statement. Analyzing the results from the same survey, Berkman and Plutzer distinguished three groups of high school biology teachers by their responses to questions about how they present evolution (as well as supposed alternatives to it) in their classrooms. NABT's statement speaks to each group.

To the 13% of teachers who present creationist perspectives favorably, NABT's statement provides a firm rebuke. The statement unequivocally rejects creation science, scientific creationism, and intelligent design as outside the scope of science and unsuitable for inclusion in the science curriculum, warning against "confusing nonscientific with scientific explanations in science instruction."

More numerous but of equal concern are the 60% of teachers who downplay evolution in the classroom. Wanting to avoid controversy and often not confident of their ability to teach evolution effectively, they are the Arnold Perlsteins of their profession. Berkman and Plutzer identified three major ways in which these teachers downplay evolution, and again NABT's statement offers appropriate correction and guidance.

First, addressing those teachers who neglect the history of life by concentrating on microevolutionary patterns and processes to the exclusion of their macroevolutionary counterparts, NABT's statement reminds them of what ought to be a big idea in any biology classroom – that all living things share a common ancestor – and says, rightly, that multiple scientific disciplines provide extensive empirical support for it.

Second, addressing those teachers who imply that teaching evolution is a necessary evil, something to understand only because it is required by the state science standards, NABT's statement reminds them that evolution is foundational to biology, and as such should be a major theme throughout the life science curriculum and prominently included in standards, curricula, textbooks, and instructional materials generally.

Third, addressing those teachers who misrepresent evolution as scientifically controversial – often with the aid of such catchphrases as "teaching the controversy" or "critical analysis" or "studying the full range of scientific views" (which often appear also in legislation intended to undermine the teaching of evolution) – NABT's statement reminds them that in the scientific community, evolution is "neither 'controversial,' nor in need of 'critical analysis.' "

The remaining 28% of teachers who present evolution in accordance with the recommendations of the scientific and science education communities deserve the gratitude of anyone who wants evolution to be taught properly. The courage of these teachers is reinforced, justified, and inspired by NABT's statement on the teaching of evolution. Reading the latest update of it, they might cheer, with Ms. Frizzle, "I couldn't have said it better myself!"

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THE *ABT* BIOMYSTERY

Although this creature is no longer with us, it still holds special meaning for the citizens of an eastern U.S. state. What is this creature? In what phylum would it be classified? What are some of its closest living relatives? What state claims this denizen of the deep and for what reason? The answer can be found in the back of this issue on page 134. (Photo taken in the Tokyo Natural Science and History Museum by W. F. McComas)

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FEATURE ARTICLE

Radiocarbon in Dinosaur Fossils: Compatibility with an Age of Millions of Years

PHILIP J. SENTER

ABSTRACT

The recent discovery of radiocarbon in dinosaur bones at first seems incompatible with an age of millions of years, due to the short half-life of radiocarbon. However, evidence from isotopes other than radiocarbon shows that dinosaur fossils are indeed millions of years old. Fossil bone incorporates new radiocarbon by means of recrystallization and, in some cases, bacterial activity and uranium decay. Because of this, bone mineral – fossil or otherwise – is a material that cannot yield an accurate radiocarbon date except under extraordinary circumstances. Mesozoic bone consistently yields a falsely young radiocarbon "date" of a few thousand to a few tens of thousands of years, despite the fact that it is millions of years old. Science educators need to be aware of the details of these phenomena, to be able to advise students whose acceptance of biological evolution has been challenged by young-Earth creationist arguments that are based on radiocarbon in dinosaur fossils.

Key Words: *dinosaurs; creationism; radiocarbon; collagen; recrystallization; carbonate; uranium; fossilization.*

Introduction

The recent discovery of radiocarbon in dinosaur fossils has the potential to generate much puzzlement, because radiocarbon has a half-life too short for measurable amounts of original radiocarbon to remain in fossils that are millions of years old. Taking advantage of the popularity of dinosaurs, young-Earth creationist (YEC) authors now proclaim in an ever-increasing number of books and DVDs that radiocarbon in dinosaur fossils demonstrates that the dinosaur fossils must be only thousands, not millions, of years old (Helfinstine & Roth, 2007; Wilson et al., 2007; Lyons & Butt, 2008; Isaacs, 2010a, b; Woetzel, 2012; Thomas, 2013, 2014; Clarey, 2015; Institute for Creation Research, 2015). Many of the other dinosaur-based anti-evolution arguments from YEC authors are less worrisome, because they are plainly absurd (e.g., Senter, 2012, 2013a, 2013b, 2017a, 2018, 2019; Siebert, 2013; Senter & Wilkins, 2013; Senter & Klein, 2014), but the absurdity in the YEC arguments based on radiocarbon is less plain. That is because students and science educators often lack knowledge of the finer details of radiocarbon dating and the fossilization process that show how radiocarbon in dinosaur bones is consistent with an age of millions of years. Appropriate responses to such YEC arguments are therefore not always at hand. Here, I present an overview of the relevant details, to arm science educators and their students with the information they need to recognize such YEC misinterpretations as incorrect.

> *"Mesozoic bone consistently yields a falsely young radiocarbon 'date' of a few thousand to a few tens of thousands of years, despite the fact that it is millions of years old."*

Radiocarbon

Radiocarbon Dating & Confounding Factors

Radiocarbon (^{14}C) is a radioactive isotope of carbon that decays into ^{14}N by emitting beta particles. Radiocarbon forms in the atmosphere after cosmic rays knock neutrons off molecules of atmospheric gases. When ^{14}N in the air is exposed to such neutrons, a nucleus of ^{14}N captures one of the neutrons and emits a proton, thereby becoming ^{14}C. The ^{14}C is incorporated into atmospheric CO_2, some of which is absorbed by oceans and lakes and some of which plants absorb during photosynthesis and animals take in when they eat plant matter. The level of ^{14}C in a plant or animal remains constant until it dies and therefore ceases to take in more ^{14}C. At death, its ^{14}C level therefore begins to drop. Because the remaining ^{14}C decays at a known rate, it is possible to calculate the date at which a plant or animal died by measuring its remaining ^{14}C. That is the basis of radiocarbon dating (Walker, 2005; Willoughby, 2016).

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Radiocarbon has a short half-life of only about 5700 years, so it is only useful for dating materials no older than about 50,000 years (van der Plicht & Palstra, 2016). Of the radiocarbon that was present in an organism at the time of its death, no measurable amount remains after 100,000 years. The fossil of an animal that died during the Mesozoic Era, tens of millions of years ago, therefore does not have any measurable amount of its original radiocarbon left.

Most science textbooks explain radiocarbon dating in no further detail than that (e.g., Campbell et al., 2009; Bergstrom & Dugatkin, 2016; Urry et al., 2017), because their goal is to provide only a general overview of it. However, the reality of radiocarbon dating is more complicated. There are several factors that can add ^{14}C to samples so that they yield falsely young ages (e.g., nuclear fallout, bacterial contamination, and contamination with coal), and there are other factors that add ^{14}C-depleted carbon to samples so that they yield falsely old ages (e.g., volcanic gases, industrial emissions, and the reservoir effect) (Table 1). However, corrective calibration techniques and other procedures can correct for all these confounding factors (Pasquier-Cardin et al., 1999; Goslar et al., 2000; Nadeau et al., 2001; McGee et al., 2004; Mihara et al., 2004; Quarta et al., 2007; Nakanishi et al., 2015; Tankersley et al., 2017; Wang et al., 2017; Yang et al., 2017). Once corrective calibrations and other corrective procedures are implemented, radiocarbon measurements yield correct dates, as has been demonstrated with radiocarbon dating of samples of known ages (e.g., Jull et al., 2018). However, as explained below, bone mineral is an exception to the rule, and there are no corrective measures that can get fossil bone mineral to generate a correct radiocarbon date.

Radiocarbon "Dates" from Mesozoic Fossils

In two 1990 articles, YEC authors reported ^{14}C analyses of Mesozoic wood and dinosaur bone. The fossils yielded radiocarbon "ages" between 9000 and 40,000 years (Dahmer et al., 1990; Fields et al., 1990). Since then, YEC authors have submitted several more Mesozoic fossil samples for ^{14}C testing. All have had enough ^{14}C to yield radiocarbon "ages" between 9000 and 50,000 years. The samples include petrified wood, coal, ammonite shells, and bone from several species of dinosaurs, including the Jurassic genera *Allosaurus* and *Camarasaurus* and the Cretaceous genera *Acrocanthosaurus*, *Edmontosaurus*, and *Triceratops* (Dahmer et al., 1990; Fields et al., 1990; Helfinstine & Roth, 2007; Snelling, 2008; Thomas & Nelson, 2015).

YEC authors consistently claim that the radiocarbon in the fossils demonstrates that the fossils are only a few thousand years old (Dahmer et al., 1990; Fields et al., 1990; Helfinstine & Roth, 2007; Lyons & Butt, 2008; Isaacs, 2010a; Woetzel, 2012; Thomas, 2013, 2014; Clarey, 2015; Institute for Creation Research, 2015; Thomas & Nelson, 2015). However, that is incorrect. Radiometric dating of Mesozoic strata using radioisotopes other than radiocarbon (e.g., $^{238}U/^{206}Pb$, $^{235}U/^{207}Pb$, $^{87}Rb/^{86}Sr$, $^{40}K/^{40}Ar$, $^{40}Ar/^{39}Ar$) shows

Table 1. Factors that affect radiocarbon dating. Factors that add ^{14}C-depleted carbon cause the samples to yield falsely old radiocarbon "ages," and factors that increase samples' ^{14}C cause the samples to yield falsely young radiocarbon "ages."

The reservoir effect: the tendency of lakes and the ocean to act as reservoirs for old carbon derived from dissolved CO_2 and carbonate rocks that are radiocarbon-depleted	Due to the reservoir effect, the carbon content of lake and marine samples is ^{14}C-depleted. The magnitude of the reservoir effect varies from one location to the next within the ocean, from one lake to the next, and from one shelled species to the next (Nadeau et al., 2001; Nakamura et al., 2007; Nakanishi et al., 2015; Wang et al., 2017). It is responsible for the famous case in which the shells of live freshwater mollusks yielded false radiocarbon "ages" of thousands of years, due to the mollusks' incorporation of radiocarbon-depleted carbonate into their shells (Keith & Anderson, 1963). It also affects radiocarbon dating of the remains of terrestrial organisms that feed on marine organisms (e.g., humans that eat seafood; Arneborg et al., 1999; Mihara et al., 2004).
Volcanic gases	Samples' exposure to this factor adds ^{14}C-depleted carbon (Pasquier-Cardin et al., 1999).
Industrial emission of fossil fuels	Samples' exposure to this factor adds ^{14}C-depleted carbon (Quarta et al., 2007; Flores et al., 2017).
Nuclear explosions and fallout	Samples' exposure to these factors increases their ^{14}C content (Gentry et al., 1998; McGee et al., 2004; Lachner et al., 2014; Yang et al., 2017).
Contamination with coal	This factor increases samples' ^{14}C content (Tankersley et al., 1987, 2017).
Contamination with bacteria or fungi	These factors increase samples' ^{14}C content (Lowe, 1989; Bonvicini et al., 2003; Tankersley et al., 2017).
Burial	This factor can increase samples' ^{14}C content via bicarbonate in groundwater and via crystallization of calcite (Zazzo & Saliège, 2011; Oslen et al., 2013; van der Plicht & Palstra, 2016).
Cremation	Radiocarbon dating of cremated bones destroys the collagen in the bones and adds ^{14}C from the wood used in the fire (Olsen et al., 2013).
Fluctuation in atmospheric ^{14}C through millennia	This factor causes elevation of ^{14}C in samples from some past time intervals and reduction of ^{14}C in samples from other past time intervals (Goslar et al., 2000).

that the sediments that entomb Mesozoic fossils are 65–251 million years old (Gradstein et al., 2004), which means that the fossils that they entomb are that old – far too old for any measurable amount of original radiocarbon to remain in the fossils. So how is it that measurable radiocarbon is indeed present in the fossils? The answer is that although the fossils have lost their *original* radiocarbon, they have since accumulated *new* radiocarbon, which yields a falsely young radiocarbon "age." To elucidate how that happens, here I review the composition of bone, what happens to it after death, its implications for radiocarbon dating, and similar implications for the radiocarbon dating of fossil wood and shells.

Bone Composition

Living bone tissue includes numerous live bone cells, blood vessels, and a mineralized mixture called *bone matrix*, which lies between the bone cells and blood vessels. The bone cells called *osteoblasts* secrete bone matrix. Osteoblasts are called *osteocytes* after they have secreted bone matrix on all sides and have become enclosed in it. The tiny space in the matrix that each osteocyte inhabits is called a *lacuna* (Eurell, 2004).

The bone matrix that osteoblasts secrete consists mainly of the protein collagen and the mineral hydroxyapatite (also spelled "hydroxylapatite" or "hydroxyl apatite"). Hydroxyapatite is a form of calcium phosphate that is bonded to hydroxide ions (OH^-). Its chemical formula is $Ca_5(PO_4)_3(OH)$. That chemical formula changes as a result of the CO_2 that the nearby cells release as metabolic waste. The body's aqueous internal environment converts the CO_2 into bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}). In the mineral component of bone matrix, that carbonate replaces so many of the phosphate and hydroxide ions in hydroxyapatite that the chemical formula of the mineral must be rewritten as $Ca_5(PO_4, CO_3)_3(OH, CO_3)$. This altered mineral is called *bioapatite*, *carbonated hydroxyapatite*, *dahllite*, or simply *bone mineral* (Hedges & Millard, 1995; Berna et al., 2004; Pfretzschner, 2004; Wings, 2004; Keenan et al., 2015; Kendall et al., 2018). Radiocarbon is present both in the collagen and in the carbonate of bone matrix.

Bone Diagenesis & Fossilization

Diagenesis is the term for physical and chemical changes to a sediment or fossil after its deposition. Bone undergoes a large amount of diagenetic change during and after burial. Bone diagenesis tends to occur in five modes: microbial activity, collagen gelatinization, permineralization, encrustation, and recrystallization.

Microbial diagenesis. During the earliest phase of bone diagenesis, microbes such as bacteria and fungi consume the bones' organic fraction (Pfretzschner, 2004). Microbial consumption of bone cells and blood vessels leaves empty voids in lacunae and Haversian canals, where osteocytes and blood vessels had been. Under some conditions, bacteria then precipitate mineral cements such as calcite (a form of $CaCO_3$), pyrite (FeS_2), siderite ($FeCO_3$), and kutnohorite ($Ca(Mn,Mg)(CO_3)_2$) into those voids (Wings, 2004; Carpenter, 2005). The infilling of voids with minerals is called *permineralization*, and it contributes to fossilization (long-term preservation).

The microbial phase is often short lived. For example, in bones submerged in bodies of freshwater, microbial activity ceases after about six months (Pfretzschner, 2004). After that, most of the organic fraction of the bone is gone (Pfretzschner, 2004).

Collagen gelatinization. Intermolecular cross-linking makes collagen a highly stable organic molecule (Antonio et al., 2011), but it eventually breaks down. Bacterial and fungal activity contribute to collagen decay (Kendall et al., 2018), and in small bones (e.g., those of rodents) in bodies of freshwater, the initial period of microbial activity destroys all of the collagen (Pfretzschner, 2004). Collagen lasts longer in larger bones (e.g., those of humans), which still retain 85–95% of their collagen a year after death (Pfretzschner, 2004). Following the period of microbial activity, the remaining collagen is attacked by abiotic factors that gelatinize the collagen by cutting it into shorter and shorter chains of peptides (Pfretzschner, 2004). Collagen breakdown occurs faster in hotter environments, in extremely acidic or extremely alkaline environments, and around cracks in the bone (Kendall et al., 2018).

The breakdown of collagen causes further diagenesis of the bone. Gelatinizing collagen soaks up water and swells, which generates cracks in the bone mineral (Pfretzschner, 2004). Collagen decay also releases sulfide (S^{-2}) ions, which leads to the precipitation of iron sulfides such as pyrite onto the surfaces of voids and cracks (Pfretzschner, 2004).

Bone mineral: preservation, permineralization, encrustation, and recrystallization. The preservation of bone mineral depends on pH and the presence or absence of buffering chemicals. Bone mineral dissolves in sediments that contain calcium aluminum phosphate minerals or have groundwater with a pH below 7. It is preserved in sediments that contain calcite and carbonated apatite and have groundwater with a pH above 8.1 (Berna et al., 2004).

If the bone mineral is preserved, three subsequent modes of diagenesis predominate in bone after the collagen gelatinization phase: permineralization (infilling of voids with minerals), encrustation (growth of minerals on external surfaces and the surfaces of cracks), and recrystallization (replacement of less-stable minerals with more-stable minerals as the minerals dissolve). At this stage, all three occur by precipitation of water-dissolved ions, without microbial help. The permineralization and encrustation may involve growth of crystals of calcite ($CaCO_3$), other carbonates, pyrite (FeS_2), barite ($BaSO_4$), and other minerals (Pfretzschner, 2004; Wings, 2004). During these processes, canaliculi that once connected adjacent osteocytes may be filled in by new hydroxyapatite or pyrolusite (MnO_2), isolating lacunae from each other (Pfretzschner, 2004; Pfretzschner & Tütken, 2011).

Recrystallization involves water-mediated exchange reactions. It is particularly prevalent at external surfaces and at cracks (Pfretzschner, 2004; Pfretzschner & Tütken, 2011). Fluorination is an important example. As it trades its hydroxide for fluoride, bone mineral is converted into francolite ($Ca_5(PO_4, CO_3)F$) and is later converted to fluoroapatite ($Ca_5(PO_4)F$). The fluorination contributes to fossilization, because it increases crystal size, which increases the stability of bone mineral (Berna et al., 2004; Kocsis et al., 2010; Kendall et al., 2018). Fossil bone of Mesozoic age always has a high fraction of francolite and fluoroapatite (Wings, 2004; Piga et al., 2011). The high stability that fluorination confers on the bone mineral in fossil bone slows down the recrystallization process but does not stop it (Berna et al., 2004; Suarez & Passey, 2014; Keenan et al., 2015). Because recrystallization continues, fossil bone has a much higher degree of recrystallization than archaeological[1] bone does (Kendall et al., 2018).

Bone recrystallization also includes processes other than fluorination. During recrystallization, some of the calcium in bone mineral is replaced by iron, manganese, zinc, strontium, sodium, and uranium (Pfretzschner, 2004). Some of the phosphate in bone mineral is replaced by metal hydroxides, which may subsequently become metal oxides (Pfretzschner, 2004). The phosphate in bone mineral can also be replaced by fluoride, chloride, or carbonate (Pfretzschner, 2004). When bone interacts with carbonate-rich water, replacement of phosphate by carbonate occurs on a larger scale and can result in replacement of most of the bone phosphate with carbonate (Fernández-Jalvo et al., 2016).

Cracking increases the rate and spread of permineralization, encrustation, and recrystallization (Pfretzschner & Tütken, 2011; Pokines et al., 2018). In sufficiently moist conditions, wet–dry cycles and freeze–thaw cycles can cause cracks in bone and are especially effective at doing so on bones at the soil–air interface and especially on the exposed side of those bones (Pokines et al., 2018). In arid environments, exposed bone cracks as it dries out (Pfretzschner & Tütken, 2011).

How New Radiocarbon Is Added to Old Bone

The amount of ^{14}C in bone drops as the bone loses organic material during the microbial decay phase and the collagen gelatinization phase. However, the amount of ^{14}C in bone then rises again as bone mineral gains new ^{14}C. There are five ways that old bone mineral gains new radiocarbon: recrystallization, permineralization, encrustation, bacterial contamination, and uranium decay.

Recrystallization, permineralization, and encrustation. Recrystallization brings new radiocarbon into bone mineral when carbonate replaces phosphate in the crystal structure of the bone mineral. The new carbonate contains ^{14}C, because it comes from bicarbonate and carbonate in groundwater, which are derived from dissolution of atmospheric CO_2, which contains ^{14}C (Olsen et al., 2008; Zazzo, 2014).

Permineralization and encrustation by calcite and other carbonates also bring new ^{14}C into bone. The purification process called *pretreatment* can remove the carbonate infillings and crusts (Zazzo & Saliège, 2011), but it cannot remove the carbonate that has been incorporated into the crystal structure of bone mineral by recrystallization.

Bacterial contamination. Old geological samples can accumulate new radiocarbon through the metabolic activity of recent bacteria and fungi, which take in atmospheric ^{14}C. The presence of their cells and their organic waste adds ^{14}C to coal samples, and methane that they excrete adds ^{14}C to petroleum if its temperature is low enough (≤77°C) to support live bacteria (Lowe, 1989; Bonvicini et al., 2003; Tankersley et al., 2017). Coal and petroleum often contain enough radiocarbon to yield falsely young radiocarbon "ages" of a few tens of thousands of years (Lowe 1989; Bonvicini et al. 2003). There is no reason to suppose that recent bacteria and fungi, if present on and in fossil bone, would not add ^{14}C to it, yielding falsely young radiocarbon "ages," as with other geological samples.

Uranium decay. Another way that new ^{14}C is added to geological samples is via the radioactive decay products of uranium. Radioactive emissions from ^{238}U add new ^{14}C by converting certain other isotopes (e.g., ^{17}O and ^{11}B) into ^{14}C (Jull et al., 1985; Bonvicini et al., 2003). In addition, some of the daughter isotopes of ^{238}U (e.g., ^{223}Ra, ^{224}Ra, and ^{226}Ra) themselves emit ^{14}C nuclei during radioactive decay (Ronen, 1997; Bonvicini et al., 2003). Buried bone readily takes up uranium via groundwater (Hedges & Millard, 1995) and concentrates it, so that fossil bone usually has a higher uranium content than the surrounding sediment (Goodwin et al., 2007; Kisleva et al., 2019).

Implications for Radiocarbon Dating of Recent Bone

Collagen. The collagen in bone matrix is the material that is usually used for radiocarbon dating of bone in archaeological samples (Olsen et al., 2013; van der Plicht & Palstra, 2016). Bone collagen can be contaminated by substances in humus and other external sources, which add new ^{14}C, yielding a falsely young radiocarbon "age." However, pretreatment removes such contaminants. Pretreated collagen therefore yields a correct age (van der Plicht & Palstra, 2016; Cersoy et al., 2018), unless it is older than 50,000 years, the upper limit for radiocarbon dating (van der Plicht & Palstra, 2016).

Bone mineral. Unlike collagen, bone mineral is usually useless for radiocarbon dating, even though the carbonate that bone mineral incorporates during life contains ^{14}C. The uselessness of bone mineral for radiocarbon dating is due to the fact that bone mineral accumulates new ^{14}C after death, yielding a falsely young radiocarbon "age." Calcite and other carbonate crystals that arrive via permineralization and encrustation add new radiocarbon (Zazzo & Saliège, 2011; van der Plicht & Palstra, 2016), but pretreatment can remove such crystals (Zazzo & Saliège, 2011). However, pretreatment cannot remove the new carbonate that becomes part of the crystal structure of bone mineral during recrystallization. Because that carbonate contains newly added radiocarbon, bone mineral yields a falsely young age when subjected to radiocarbon analysis. The older a sample is, the greater the difference between the actual age and the false age that results from recrystallization. The magnitude of the difference between the actual age and the radiocarbon "age" of the mineral jumps upward dramatically in samples older than about 10,000 years (Zazzo, 2014) and is hugely amplified in samples older than about 35,000 years (van der Plicht & Palstra, 2016). As a result, samples of bone mineral from bone that is tens of thousands of years old yield false "ages" thousands of years younger than the actual age of the bone, even after pretreatment (Zazzo, 2014).

There are two exceptions to the rule that bone mineral consistently yields a falsely young age. Cremated bone is an exception, because the heat of cremation recrystallizes the bone mineral into a more stable form that is resistant to further recrystallization (Olsen et al., 2013). The other exception is bone that has been preserved in arid areas that have remained arid for the duration of the bone's presence there, because infiltration of ^{14}C via groundwater-borne minerals doesn't happen where there is no groundwater (Zazzo & Saliège, 2011).

Implications for Radiocarbon Dating of Fossil Bone

The fossil bone in Mesozoic samples suffers from problems that make attempts at radiocarbon dating pointless. First, as previously pointed out, radiometric dating of Mesozoic strata using radioisotopes other than radiocarbon shows that Mesozoic fossils are 65–251 million years old (Gradstein et al., 2004), far too old for any measurable amount of original radiocarbon to remain. Second, the collagen in Mesozoic bone has usually long since decayed away and is therefore unavailable for radiocarbon dating. Even when original collagen is present, it is millions of years too old to contain measurable amounts of original radiocarbon. Third, the processes of recrystallization, permineralization, encrustation, bacterial contamination, and uranium decay add new ^{14}C to old bone, causing it to yield a falsely young radiocarbon "age."

Recrystallization. Fossil bone continues to behave as an open system and experiences recrystallization throughout its existence. Chemical analyses have confirmed that late in its existence, Mesozoic bone continues to accumulate rare earth elements (Kocsis et al., 2010) and carbonate (Piga et al., 2011; Keenan et al., 2015) and that its continued recrystallization includes the addition of new carbonate even during the recent period of erosion that exposes the bone-containing sediment (Suarez & Passey, 2014). That erosion is what enables paleontologists to visually spot the bone-containing deposit and prompts them to excavate the bones. It therefore stands to reason that any Mesozoic bone that has been found and excavated has recently accumulated new carbonate, which adds new ^{14}C, which in turn accounts for the falsely young radiocarbon "age" that every Mesozoic bone that has been subjected to radiocarbon "dating" has yielded. As previously mentioned, pretreatment can remove carbonate that has arrived via permineralization and encrustation, but it cannot remove carbonate that has been incorporated into the crystal structure of the bone mineral by recrystallization. That new carbonate includes new ^{14}C, yielding a falsely young radiocarbon "age."

The two exceptions (cremation and arid environments) to the rule that bone mineral consistently yields a falsely young age do not apply to Mesozoic bone. Mesozoic bone was not cremated, nor is it typically entombed in places that are devoid of groundwater through the duration of its entombment. Although Mesozoic bones are often discovered in places that are currently arid most of the year, such places (e.g., western North America, the origin of all Mesozoic dinosaur bone that has thus far been subjected to radiocarbon "dating") usually experience rain at some time during the year, exposing shallowly buried fossil bones to waterborne bicarbonate and carbonate ions that introduce new radiocarbon into the bone mineral through recrystallization.

All of the fossil bone that YEC teams have subjected to radiocarbon analysis has included bone mineral. Such samples are therefore useless for obtaining an accurate age by means of radiocarbon. Although at least some YEC teams subjected the fossil samples to pretreatment to remove calcite that had arrived by permineralization and encrustation (Snelling, 2008; Thomas & Nelson, 2015), pretreatment cannot remove the carbonate that has been incorporated into the crystal structure of bone mineral via recrystallization and therefore cannot remove the ^{14}C that has arrived via that carbonate. Therefore, none of the radiocarbon "ages" that YEC teams obtained for fossil bones are the bones' true ages. Instead, all such radiocarbon "ages" are falsely young. This means that the bones that they found to yield radiocarbon "ages" of over 40,000 years (Fields et al., 1990; Helfinstine & Roth, 2007; Thomas & Nelson, 2015) are much older than 40,000 years, which contradicts their own assertion that the Earth and the ancestors of all the life-forms on it came into existence only about 6000 years ago.

Bacterial contamination. The interior of Mesozoic bone does not usually harbor bacteria, because most of its organic fraction has usually long since decayed away, leaving little for bacteria to use for food. Nonetheless, there are some cases in which Mesozoic bone is known to have harbored recent bacteria. Liquid chromatography and mass spectrometry confirmed the presence of chemicals made by recent soil-dwelling bacteria within a bone from a Cretaceous dinosaur (Asara et al., 2007). Visual inspection via microscopy confirmed the presence of bone-boring cyanobacteria on the surface of a bone from a Cretaceous mosasaur, and amplification via polymerase chain reaction confirmed the presence of bacterial DNA in the bone (Lindgren et al., 2011). Soft material from the bone of a Cretaceous turtle had the spectrographic signature of bacterial biofilm, in addition to morphological features consistent with bacterial cells and with troughs made by bacterial locomotion through biofilm (Kaye et al., 2008). The bacterial biofilm in the Cretaceous turtle bone was subjected to radiocarbon analysis and was found to contain a "greater than modern" (too young to accurately date) amount of radiocarbon, indicating that the contamination had occurred very recently (Kaye et al., 2008). As these examples show, Mesozoic bone can undergo bacterial contamination, a phenomenon that is known to introduce new ^{14}C to geological samples, contributing to a falsely young radiocarbon "age."

Uranium decay. Of the nine dinosaur bone specimens that were subjected to radiocarbon analysis in the YEC study by Thomas and Nelson (2015), four came from the Hell Creek Formation (Thomas & Nelson, 2015), which is uranium-rich (Kipp et al., 2009). Two came from the Lance Formation (Thomas & Nelson, 2015), which is also uranium-rich (Verstraeten et al., 2001). Also, two of the dinosaur genera that previous YEC teams subjected to radiocarbon analysis – *Allosaurus* and *Camarasaurus* (Dahmer et al., 1990; Helfinstine & Roth, 2007) – are from the Morrison Formation. The Morrison Formation is uranium-rich (Chenoweth, 1985), and dinosaur bones from it are notorious for containing large amounts of uranium (Gillette, 1994; Hubert et al., 1996). The dinosaur bone deposit at Dinosaur National Monument, the source of an unidentified dinosaur bone that was also subjected to radiocarbon analysis (Helfinstine & Roth, 2007), is also part of the uranium-rich Morrison Formation. As previously noted, ^{14}C is one of the decay products of ^{238}U and of some of its daughter isotopes.

Implications for Radiocarbon Dating of Fossil Wood & Shells

Fossil wood. YEC teams have reported that Mesozoic petrified, carbonized, and coalified wood yielded radiocarbon "ages" between 11,000 and 50,000 years (Helfinstine & Roth, 2007; Snelling, 2008; Thomas & Nelson, 2015). Petrified wood often retains a substantial fraction of its original organic content (Jiang et al., 2018), which at first would seem to make it conducive to radiocarbon dating if the YEC position that the wood is only a few thousand years old is correct. However, as with fossil bone, petrified wood undergoes recrystallization even millions of years after the death of the organism, often has absorbed a substantial amount of uranium, and often contains calcite and other carbonates that were not part of the original tree (Jiang et al., 2018; Kuczumow et al., 2019). Because all those factors introduce new ^{14}C into such fossils, attempts to determine the ages of petrified wood by using radiocarbon are useless.

Similarly, carbon-containing compounds such as carbonates are introduced into coalified or partially coalified fossil wood by percolation of groundwater, infilling of fractures, recrystallization of mineral inclusions, mineralization of the wood after coalification, and meteoric processes during weathering (Yudovich, 2003; Dawson et al., 2012; Ward, 2016). Coal also absorbs and concentrates uranium (Yang, 2007; Havelcová et al., 2014), which adds new ^{14}C as a decay product.

Ammonite shells. Snelling (2008) reported that Cretaceous ammonite shells yielded radiocarbon "ages" between 36,000 and 49,000 years. However, fossil carbonate shells, like fossil bone and wood, are open systems that accumulate new carbonate, and hence new ^{14}C, via groundwater-mediated encrustation and recrystallization (Ayling et al., 2017; Graf et al., 2018; Javanbacht et al., 2018). Fossil carbonate shells also readily absorb uranium (Ayling et al., 2017), which adds new ^{14}C as a decay product.

○ Conclusions

Mesozoic dinosaur bones are millions of years old, as demonstrated by radiometric dating with radioisotopes other than ^{14}C. Radiocarbon in Mesozoic dinosaur bones is new, not original to the bone. Its addition to the bones yields the false appearance of a young age. The new radiocarbon in fossil bone mineral is in carbonate that is incorporated into the crystal structure of bone mineral during recrystallization and cannot be removed by pretreatment. In some cases, bacterial activity or the radioactive decay products of uranium add even more radiocarbon to the bone.

○ Further Comments

Teachers who encounter students who have been misled by YEC arguments that are based on radiocarbon in dinosaur bones are encouraged to direct such students to the information presented here. However, YEC publications have generated a plethora of other anti-evolution arguments, and it would be useful to be able to counter those as well. It is therefore worthwhile to note that there are four recent books that together refute nearly all of the YEC arguments that have been published thus far: Isaak (2007), Prothero (2007), Kane et al. (2016), and Senter (2019). Such resources could be useful for educating both teachers and students and for inoculating students against future exposure to YEC arguments.

Additionally, for students who profess loyalty to the Bible, it would be useful to know that several passages in the Old and New Testaments instruct against taking Genesis literally and therefore that the Bible itself does not support the YEC view. Such passages are reviewed in Senter (2019) and are partially reviewed in Senter (2016). It would be worthwhile for teachers to know of such resources, so as to direct students to them when appropriate. It is legal, at least in the United States, to address religious concerns that students bring up in science classes, as long as the teacher does not endorse one religious view over another (Hermann, 2013). Studies on conceptual change suggest that addressing such concerns may be effective in helping students feel comfortable accepting evolution and an old Earth if their objections to such concepts are based on religious concerns (Senter, 2017b). Such help could be a useful supplement to science-based refutations of YEC arguments such as those presented here regarding radiocarbon in dinosaur bones.

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Note

1. The terms *archaeology* and *paleontology* are often confused. *Archaeology* is the study of human material cultures. It deals with samples that are a few thousands of years old or younger. *Paleontology* is the study of fossils. It deals with samples that are tens of thousands of years old or older, including samples that are millions or billions of years old. The crossover discipline of *paleoarchaeology* is the study of the material cultures of very ancient humans and their extinct relatives. It deals with samples that are 10,000 to 15 million years old.

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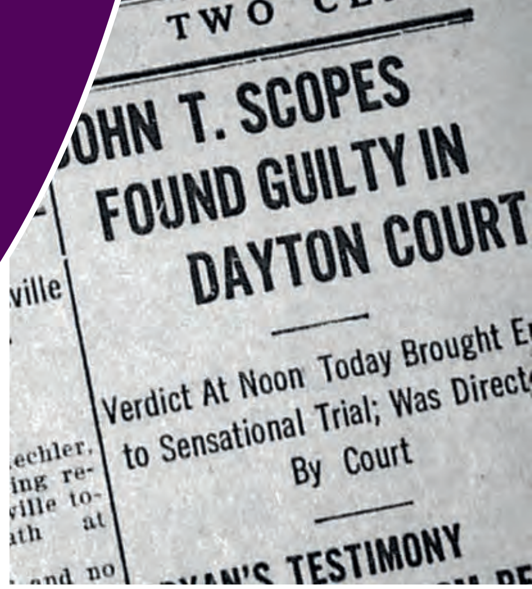
FEATURE ARTICLE

The Long & Lingering Shadow of the Scopes Trial

RANDY MOORE



Abstract

Just before his death in 1970, John Scopes claimed that his famous trial "had no other effect upon my family" than his sister Lela losing her teaching job in Paducah, Kentucky. He was wrong. My interviews with John Scopes's family members and descendants – most of whom have never talked about their famous relative until now – reveal that the legacy of the Scopes Trial continues.

Key Words: *John Scopes; Scopes Trial; evolution; biology education.*

○ Introduction

For decades, biology teachers and others from around the world have visited Dayton, Tennessee, to learn about the Scopes Trial and its associated issues and events. While in Dayton, these visitors photograph the famous courthouse, stand in the courtroom where John Scopes was convicted (Figure 1), and look for the myriad other places associated with the trial – for example, where Clarence Darrow questioned William Jennings Bryan, where Scopes lived, and where Bryan died (Moore, 2016).

Although Scopes's famous trial produced no legal precedents, its events and legend have influenced virtually all of the many subsequent court cases involving the teaching of evolution and creationism in U.S. public schools. For example, in *Epperson v. Arkansas* (393 U.S. 97, 1968), the U.S. Supreme Court cited "the celebrated Scopes case" and, nearly two decades later in *Edwards v. Aguillard* (482 U.S. 578, 1987), referred to "the celebrated Scopes Trial of 1925" and "the legend of *Scopes v. State*." More recently, in *Kitzmiller v. Dover Area School District* (400 F. Supp. 2d 707, 2005), federal judge John E. Jones III cited "the Scopes 'monkey trial'" in his decision.

"One thing is clear: John Scopes was wrong. His trial has affected – and continues to affect – many people."

The Scopes Trial also had important consequences in Dayton. For example, the trial (and Bryan's death five days after it concluded) helped spur the formation of Bryan College, which continues to thrive in Dayton. Several individuals associated with the trial were also affected, including Scopes and his family. For example, after enrolling in graduate school at the University of Chicago, John Scopes – in need of money – applied for a fellowship to pursue a PhD in geology. The university president, apparently equating Scopes's advocacy of teaching evolution with atheism, dismissed Scopes's application in a letter, saying, "Your name has been removed from consideration for the fellowship. As far as I am concerned, you can take your atheistic marbles and play elsewhere" (Scopes & Presley, 1967, p. 240). The cash-strapped Scopes dropped out of school and never received a graduate degree (Creviston, 2019).

Another relatively well-known result of the Scopes Trial was that Scopes's youngest sister, Lela V Scopes (1896–1989), lost her teaching job in Paducah, Kentucky, because of "her belief in evolution" (Scopes & Presley, 1967, p. 243; Editorial, 1989; Figure 2). Lela was soon rehired in New York, where she continued her successful teaching career. Despite her treatment, Lela never complained about what happened to her in Paducah. After moving back to Kentucky later in her life, Lela simply lamented that it was "too bad there was a conflict" between science and religion (Shelton & Smith, 1979).

The Scopes Trial has been linked with several social ideals (e.g., religious alternatives, nativism, feminism; see Moran, 2002, pp. 171–212), but – according to virtually all accounts – the personal impact of the Scopes Trial on Scopes's family ended with Lela's firing. Indeed, later in his life, even John Scopes claimed that "as far as I know, the trial had no other effect upon my family than [Lela's] decision at Paducah" (Scopes & Presley, 1967, p. 234). Given the notoriety of Scopes's trial, I questioned this, but found no conflicting information

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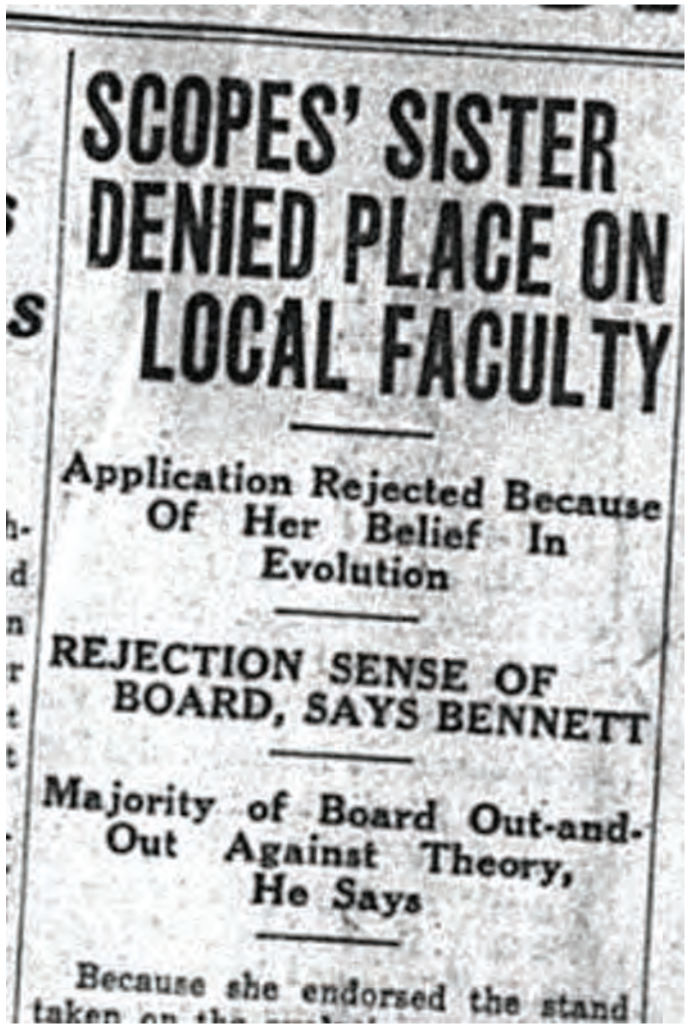
Figure 1. On Tuesday, July 21, 1925, John Scopes stood to hear the verdict at his famous trial in Dayton, Tennessee (photo courtesy of Bryan College).



SCOPES' SISTER DENIED PLACE ON LOCAL FACULTY

Application Rejected Because Of Her Belief In Evolution

REJECTION SENSE OF BOARD, SAYS BENNETT

Majority of Board Out-and-Out Against Theory, He Says

Because she endorsed the stand

Figure 2. John Scopes's sister, Lela, was fired from her teaching job in Paducah, Kentucky, because she would not denounce her brother's views about teaching evolution.

in written accounts of the trial's impact on John Scopes's life after Dayton. There were mentions of what happened to Lela, but other members of John Scopes's family were never quoted or cited, and I wondered what they might say (if anything) about the impact of their famous relative's famous trial if given the opportunity to speak for themselves.

○ An Overlooked Source of Information

During the past eight years, I've visited multiple times with a variety of descendants, friends, and colleagues of John Scopes and his wife, Mildred Scopes (Moore, 2019). For most of Scopes's relatives, my questions were the first they had ever been asked about John Scopes by a researcher, and I was only the second researcher to contact John Scopes Jr. about his father's trial.

During my interviews, I heard countless stories, studied family scrapbooks, and learned much new information about John Scopes. (One of the meetings with John Scopes Jr. also coincided with a family reunion.) For the topics presented here, the stories were consistent and informative.

One thing is clear: John Scopes was wrong. His trial *has* affected – and continues to affect – many people. For example, when John Jr. (b. 1932) and his younger brother, William "Bill" Scopes (1936–2016), tried to join the military, their inductions were delayed (e.g., by more than seven months for John Jr.) by their father's association with Clarence Darrow and the ACLU.

Similarly, several of John Scopes's great-grandnieces today are proud of what John did in Dayton and quickly pointed out that their families "backed Uncle J.T." However, they often quickly added comments such as "His trial was never discussed much" and "It was not a good thing for our family." Great-grandniece Nancy Rose told me, "I think our disconnect with the church might have been the result of things that happened" in Dayton. Similarly, great-grandniece Lisa Rennegarbe – who first realized that her uncle was "a big deal" when she saw a report of his death on the evening news – admitted that the trial "was not a positive thing for our family" and that family members "just get tired of defending what Uncle J.T. did."

○ What's in a Name?

Even the name "Scopes" in John's descendants has generated controversy. For example, Walter Scopes Gilliam (1916–1982), a son of Nannie Mae Scopes Gilliam (1888–1988; John Scopes's oldest sister), became a deacon in Olivet Baptist Church in Paducah, despite the fact that – according to his wife – "the name 'Scopes' caused problems in the church." The negative view of the Scopes name by some in the congregation was most evident in a hallway of the church, where pictures of all of the deacons were displayed above their full names. The only exception was Gilliam, whose name was listed simply as "Walter Gilliam" (i.e., without his middle name, Scopes, or even an "S." abbreviation). The family, and others, noticed – and knew the reason for – the church's exceptional treatment of his middle name.

Susan Brooks, John Scopes's great-grandniece and Walter Scopes Gilliam's granddaughter, attended Heath Middle School in Paducah in 1982. On the first day of school, Susan's seventh-grade teacher pulled Susan aside and told her that she was "not going to put up with any [Scopes] trouble." When Susan told her mother about the incident, her mother admitted that "your grandfather had trouble with his name his whole life."

Similarly, in the early 2000s, a great-grandniece of John Scopes (who wishes to remain anonymous) and her husband were expecting a child. They planned to continue a family tradition by using the name of one of their ancestors as their child's middle name. When a Chattanooga church learned that they were considering using "Scopes" as the child's middle name, a group of concerned church members formed a "prayer group" to pray about the issue. For several weeks, a barrage of e-mails and phone calls tried to convince the couple that including "Scopes" in their child's name would "burden" the child for its entire life and might, in fact, be ungodly. They ultimately decided not to include "Scopes" in their child's name.

Historian Adam Shapiro (2013, p. 4) noted that the Scopes Trial and the historically inaccurate (but popular) movie *Inherit the Wind* "cemented the name Scopes becoming a label of derision employed by those who saw evolution as an irreligious and immoral doctrine." Great-grandniece Susan Brooks, after noting "the generally negative association of the Scopes name throughout the Bible Belt," added a personal affirmation of Shapiro's conclusion when she explained that her family

> simply had to adjust to the disapproval and suspicion by some in the community. Even today when the trial is discussed, it is not uncommon for family members to attempt an explanation of the distance between faith and science, or for some to begin a discussion with phrases like, "The Scopes are not atheists," as a way to remove the perceived ideological distance between us and them.

Ironically, Lela Scopes and her sister, Ethel Scopes Clark (1889–1962), later became Bill and John Jr.'s de facto parents when John and Mildred were battling alcoholism and (according to John Jr.) "pawned us off on my father's sisters" for several years. (For two of the years when the boys were living away from their parents, the boys attended the Paducah school from which Lela had been fired.) As John Jr. told me recently, "I don't know where we'd be without Lela. She saved us."

Bill and John Jr. lived with Lela and Ethel for three years, during which time Lela paid all of the boys' expenses. Later, Lela paid the college fees for both boys, as well as paying for the Paducah funeral services and tombstone for John and Mildred Scopes. Lela – whom John Jr. reveres as "the greatest person I've ever met" – also added the epitaph on her famous brother's tombstone: "A Man of Courage" (Figure 3).

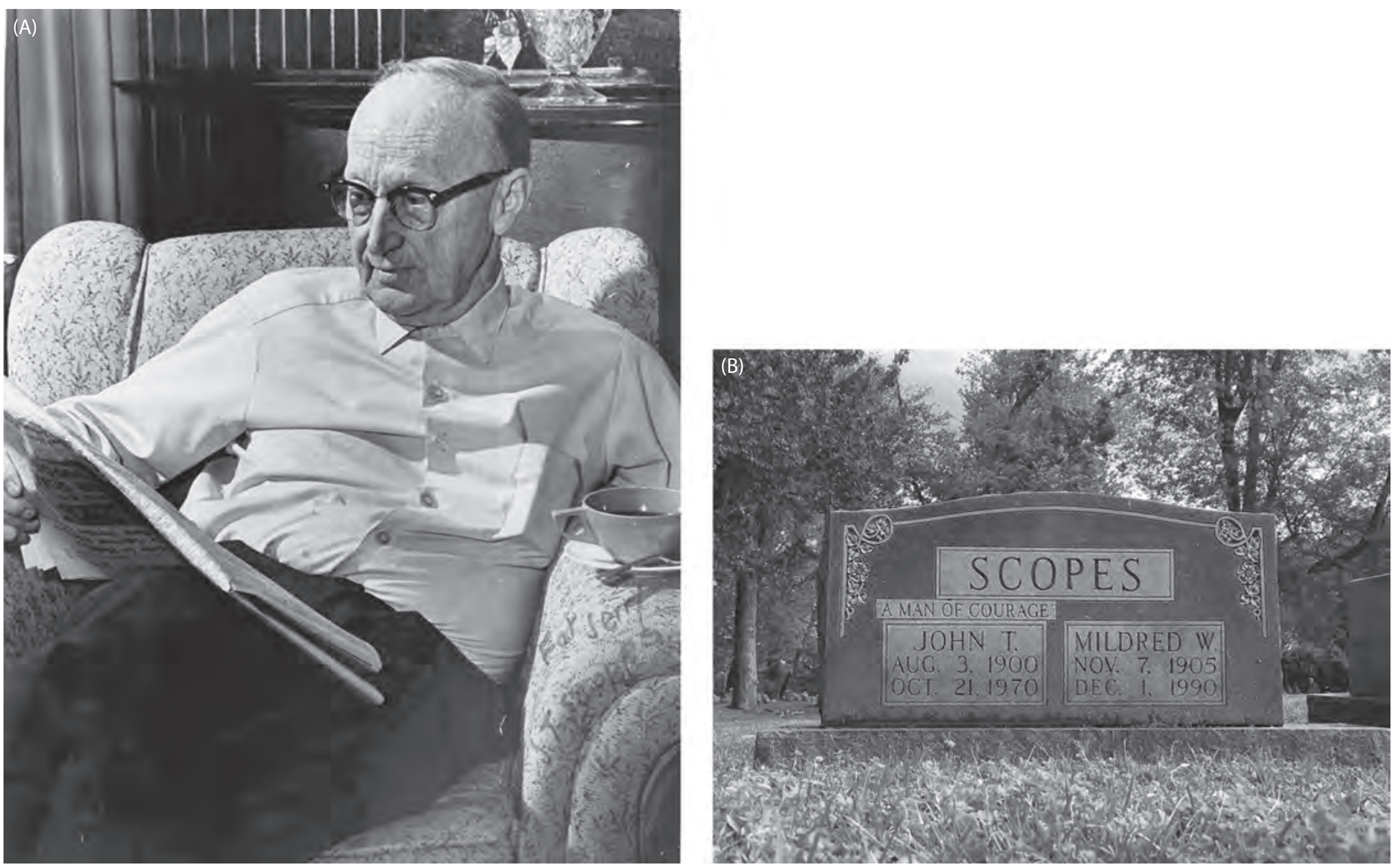


Figure 3. (**A**) John Scopes in his home in Shreveport, Louisiana, around 1965 (photo courtesy of Jerry Tompkins). (**B**) John Scopes died in 1970 and is buried in Paducah, Kentucky, beneath the inscription "A Man of Courage." Today, his legendary trial continues to affect his descendants (photo by Randy Moore).

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Moore, R. (2019). Personal communications. These descendants, and the dates of my most recent meetings with them, include John Scopes Jr., a son of John Scopes, and his wife Jan, in Lafayette, Louisiana, May 12–15, 2019; William "Bill" Scopes, a son of John Scopes, and his wife Jackie, in Guntersville, Alabama, March 12–14, 2016; Jackie Scopes, John Scopes's daughter-in-law, in Guntersville, Alabama, November 19, 2016; Nancy Rose, John Scopes's great-grandniece, in Dayton, Tennessee, July 19–20, 2016; Susan Brooks, John Scopes's great-grandniece, and her husband, Chris, in Dayton, Tennessee, July 18–20, 2019; Richard Heflin, John Scopes's great-grandnephew, in Paducah, Kentucky, April 21–24, 2017; Lisa Rennegarbe, John Scopes's great-grandniece, in Bowling Green, Kentucky, June 2–5, 2019; Jeanette Gilliam Travis, John Scopes's grandniece, in Paducah, Kentucky, April 21–24, 2017. I also met several times with acquaintances of John Scopes, including Jim Presley (John Scopes's biographer) in Texarkana, Texas, on February 6, 2016; Jerry Tompkins (John Scopes's editor) in Dayton, Tennessee, on July 19–20, 2016; and Susan Epperson (whose court case, *Epperson v. Arkansas*, overturned the law used to convict John Scopes in Dayton) and her husband, Jon, in Larkspur, Colorado, on November 1–2, 2018. Before and after these meetings, I also corresponded with most of these people via e-mail, telephone, and/or texts. I thank all of these friends for sharing their time, stories, and mementos with me.

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FEATURE ARTICLE

Understanding of Evolution Law among K–12 Public School Teachers

RONALD S. HERMANN, JOSEPH W. SHANE, LEE MEADOWS, IAN C. BINNS

Abstract

Despite frequent litigious interactions between science and religion, when it comes to the teaching of evolution, relatively little is known about public school teachers' understanding of the associated legal issues. The present study expands on Moore's (2004) survey by obtaining more information about respondents, surveying teachers from multiple states, including teachers of all grade levels, and including "I don't know" as an option on the original survey developed by Moore. The survey was completed by 208 teachers from 42 states. Findings include a detailed portrait of teachers' understanding of evolution-related laws and the time they devote to teaching evolution. Our results indicate that the majority of surveyed teachers devote >13 hours of instruction per class semester to evolution and teach evolution either as a unifying theme throughout the class or as a unit of instruction. The responses indicate that a majority of the teachers surveyed possess a sufficient understanding of legal issues but lack a sufficient understanding of the more nuanced aspects of evolution case law. The findings indicate the need for improved preservice and inservice instruction that addresses evolution case law, emphasizing the legal parameters that teachers should adhere to when teaching evolution.

Key Words: *evolution; law; K–12 teachers.*

○ Introduction

Despite frequent litigious interactions between science and religion, when it comes to the teaching of evolution, relatively little is known about public school teachers' understanding of the associated legal issues. Challenges to the teaching of evolution in public school science classes have proliferated since the Scopes Trial (Hermann, 2008). Moreover, the history of case law indicates that each new ruling often results in opponents devising new strategies for dismantling evolution instruction (Hall & Woika, 2108). Although the scientific community overwhelmingly accepts evolution (Wiles, 2010), the rate of acceptance of evolution in the United States is low compared to other countries (Miller et al., 2006), and those who do not accept evolution continue to challenge its teaching. These challenges require public school science teachers to stay current in both biology content knowledge and their understanding of what can and cannot be legally done in the classroom (Hermann, 2013). Anti-evolution challenges have taken on many forms over the past few decades, including "creation science," "intelligent design," and "academic freedom" legislation (Binns, 2013). At the secondary level, where the theory of evolution is expected to be taught in most states, science teachers continue to report that they avoid instruction on evolution or teach potentially unconstitutional alternatives to evolution (Berkman & Plutzer, 2011).

> *"Knowing what legally can and cannot be done when teaching evolution can inform teachers' practice and help them navigate conversations with students either individually or in groups."*

Many teachers may not be fully aware of the extent to which their classroom practices are in accordance with the legal parameters related to the teaching of evolution (Moore, 2004). In 2004, Moore reported the results of a survey of 103 high school biology teachers from Minnesota. He found that overall, these teachers had a good understanding of the legal issues associated with teaching evolution and creationism, though 27% believed they had the choice to teach creationism in the science curriculum. Further, 29% of the teachers thought it was still a crime to teach evolution in some parts of the United States. There has been little research on teachers' understanding of legal aspects of evolution since Moore's publication. As part of a multifaceted study, Vaughn and Robbins (2017) found a shift in preservice teachers' opinions after an introductory biology course in which they were required to read and write about relevant Supreme Court cases. The preservice teachers' views became significantly

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more supportive of the teaching of evolution, but the authors did not measure their understanding of evolution-related legal cases.

Studies of legal issues surrounding the teaching of evolution have largely been limited to biology teachers or biology courses at the middle and high school levels. However, salient aspects of evolutionary theory are found in science classes from elementary school through high school. Teaching out of field is a general problem for science teachers, with a recent study indicating that only 36% of new science teachers are teaching only in their primary field of study (Nixon et al., 2017). Many of those teaching evolution may not have completed a life science or biology major. At the elementary level, 34% of teachers have taken courses in life, earth, and physical sciences; at the middle school level, 40% of life science/biology teachers have a degree in the field; and at the high school level, 63% of life science/biology teachers have a degree in the field (Banilower et al., 2018). The prevalence of teaching out of field may indicate that many life science/biology teachers have not had the opportunity to complete course work emphasizing evolution, evolution-specific pedagogy, or the legal aspects of teaching evolution.

The present study explores K–12 teachers' current views on teaching evolution and their knowledge of legal cases. Since Moore's (2004) study, there have been additional challenges to the teaching of evolution and, hence, additional media coverage of the topic. Thus, teachers may be more aware of the legal issues than they were 15 years ago. Our primary purpose here is to provide a snapshot of the current state of evolution teaching across the nation. Thus, we explored the amount of time teachers devote to teaching evolution and the extent to which that may be related to their understanding of evolution-related laws. We also explored differences in understanding of those laws in relation to years of teaching experience. Finally, we explored differences in understanding of evolution-related laws among elementary, middle, and high school teachers.

○ Study Design

We began by developing a survey that expands upon the one developed by Moore (2004). The survey contains a total of 32 questions, including 20 related to case law; other questions ask in what state or territory the respondent teaches, what the participant teaches and at what grade level, whether they teach life science/biology topics and the time they devote to evolution-related topics, and (as a follow-up) why they *do not* teach evolution. Nineteen of the 20 questions assessing participants' knowledge of legal aspects of teaching evolution are taken from Moore's (2004) survey. We removed Moore's question "If the government uses tax money to produce public exhibits that promote evolution, must it also provide funds to produce exhibits that promote creationism?" because it seemed to be outside the realm of the classroom teacher. In its place we added question 20 ("Is teaching intelligent design unconstitutional?"), about the decision in *Kitzmiller v. Dover Area School District*, a case decided a year after Moore's publication.

We sent a draft of our survey to four teachers (two high school, one middle school, and one elementary) to solicit feedback. On the basis of comments and suggestions from these four teachers, we revised several questions and answer choices. One of the most notable changes was the inclusion of "I don't know" as a response for the legal questions, whereas Moore's original survey included only "Yes" and "No" options. The logic behind this change is that some teachers simply didn't know an answer and told us they would be guessing.

We disseminated the final version of our survey online as a Google form that was blinded so that we did not have the ability to identify or follow up with respondents. We sought to obtain a national sample of K–12 public school teachers, whereas Moore's original study was focused on high school biology teachers in the state of Minnesota. We solicited K–12 teachers' participation in a variety of ways. Individual messages were sent to program alumni encouraging them to complete the survey and disseminate it among their colleagues. We also posted messages about the survey on several social media pages related to teaching science generally or biology specifically. We also posted recruitment messages to the elementary-specific and biology-specific listservs of the National Science Teachers Association and an NGSS biology Facebook page with >7000 members. Our recruitment message stated that we "are interested in learning more about the instructional approaches used by teachers and the extent to which teachers are informed about legal issues related to teaching evolution." While we encouraged all K–12 public school teachers to complete the survey, one limitation of this approach is that it may have minimized the number of responses we received from teachers who do not teach evolution. However, this limitation likely existed for other, similar studies. For example, Berkman et al. (2008) had a 48% response rate for their 2007 survey, which contained questions about teaching evolution and personal attitudes toward evolution and creationism. Similarly, Rutledge and Mitchell (2002) had a 56% response rate for their survey, which included items about teaching of evolution and academic background. A response rate of 50–56% could similarly result in a sample of participants more inclined to teach evolution. In each of these studies and the present study, some teachers who avoid evolution or teach alternatives did respond to the survey. However, our sample may be biased toward including teachers who are more inclined to teach evolution, given their willingness to respond to a survey about teaching evolution. Despite this limitation, in our sample of teachers, 9.5% either avoid teaching evolution or teach alternatives to evolution. The survey was limited to K–12 public school teachers in the United States. We received 212 responses, but two were blank and two others were from teachers who were not teaching a class that would include evolution as a topic, leaving 208 teachers who have completed the survey.

○ Results

As noted, this study expands on Moore's (2004) work by sampling K–12 public school teachers across the United States. The teachers who responded to the survey teach in public schools in 42 states. The states most highly represented are Maryland (21), California (20), and Illinois (10), with the remaining states each represented by nine or fewer teachers. Thirty-four teachers were located in the Southeast, where fundamentalist religious beliefs are common (Goldston & Kyzer, 2009). The majority of the 208 respondents, 65.8%, teach high school; 17.1% teach middle school; and the remaining 17.1% teach elementary school. The respondents represent a range of teaching experience, including 20.8% who have taught for 11–15 years, 19.8% who have taught for 6–10 years, 16.4% who have taught for 3–5 years, 15.9% who have taught for 16–20 years, and 8.7% who have taught for ≥31 years. Only 4.3% of the respondents have taught for ≤2 years.

When asked how much time per semester they devote to teaching evolution, the clear majority, 41.3%, indicated that they devote ≥17 hours of instructional time to teaching evolution, followed by 18.9% who reported devoting 13–16 hours; 8.5% reported devoting no time to teaching evolution; 6% reported allocating 2–4 hours; and 4% reported allocating less than an hour to the topic. Among those who do not teach evolution, 17.9% indicated that it is not in the curriculum, 1.8% said they want to minimize or avoid conflict, and 0.9% cover the topic but do not refer to it as evolution.

Most of the teachers surveyed (48.3%) indicated that evolution is a unifying topic throughout the course, whereas 31.8% teach evolution as a unit like any other topic, 9.0% do not cover evolution, and 10.9% use phrases like "change over time" instead of "evolution."

The modified Moore (2004) survey is reliable with our population of teachers (Chronbach's $\alpha = 0.740$). For the 20 questions on evolution-related law (Table 1), an average of 60.82% of the responses were correct, 10.68% were incorrect, and 28.50% indicated that the teacher did not know the answer to the question. Among his sample of Minnesota biology teachers, Moore found that an average of 78.45% of the questions were answered correctly. The lower rate of correct responses in our sample may be due to the broader (42-state) region covered, the broader sample population of K–12 teachers, and the inclusion of "I don't know" as a response choice.

Quite a few of the questions and responses reported in Table 1 stand out either because a high percentage of the responses were incorrect or because a high percentage of teachers responded that they do not know the answer. More than half the teachers do not know if it is still a crime to teach evolution anywhere in the United States today (question 3), that the court determined that creation science has no scientific merit (question 8), or whether the Supreme Court has endorsed the teaching of "evidence against evolution" (question 12). Because of the high percentage of teachers responding that they do not know the answer, the percentage of teachers correctly answering those three questions was <50%. Additionally, <50% of the teachers correctly responded to questions asking if science teachers could be requested by school administrators to read a disclaimer (question 14), if science teachers could teach creationism if their school district adopts a book promoting it (question 15), if the Scopes trial struck down laws that banned the teaching of human evolution (question 18), if Scopes was

Table 1. Percentage of survey participants who chose each of the three possible responses to questions about legal issues related to the teaching of evolution (asterisk indicates correct response).

Question & Supporting Case Law	Yes	No	I Don't Know
1. Must science teachers who teach evolution give equal time to creationism? (McLean v. Arkansas Board of Education, 529 F. Supp. 1255 [E.D. Ark. 1982]; Edwards v. Aguillard, 482 U.S. 578 [1987]; Daniel v. Waters, 515 F. 2d 485 [6th Cir. 19751])	2.9	88.3*	8.7
2. Can science teachers who teach evolution give equal time to creationism? (McLean v. Arkansas Board of Education, 529 F. Supp. 1255 [E.D. Ark. 1982]; Edwards v. Aguillard, 482 U.S. 578 [1987])	10.3	72.5*	17.2
3. Is it still a crime to teach evolution anywhere in the United States today? (Epperson v. Arkansas, 393 U.S. 97 [1968]; Wright v. Houston Independent School District, 366 F. Supp. 1208 [S.D. Tex. 1972], aff'd, 486 F.2d 137 [5th Cir. 1973], cert. denied sub. nom.; Brown v. Houston Independent School District, 417 U.S. 969 [1974])	13.3	35.3*	51.2
4. Students and their parents claim that evolution offends and is incompatible with their religious beliefs. Must teachers modify their teaching to accommodate the student's right to religious freedom? (Wright v. Houston independent School District, 366 F. Supp. 1208 [S.D. Tex. 1972], aff'd, 486 F2d 137 [5th Cir. 1973], cert. denied sub. nom.; Burstyn v. Wilson, 343 U.S. 495, 505 [1952]; Epperson v. Arkansas, 393 U.S. 97 [1968])	5.8	77.7*	16.5
5. Can the government use tax money to promote the teaching of evolution? (Willoughby v. Stever, Civil Action no. 1574-72 [D.D.C. 25 August 1972], aff'd mem., 504 R2d 271 [D.C. Cir. 1974], cert. denied, 420 U.S. 927 [1975])	70.2*	6.3	23.4
6. If the government uses tax money to produce science textbooks that promote evolution, must it also provide funds to promote textbooks that promote creationism? (Willoughby v. Stever, Civil Action no. 1574-72 [D.D.C. 25 August 1972], aff'd mem., 504 R2d 271 [D.C. Cir. 1974], cert. denied, 420 U.S. 927 [1975])	3.9	84.1*	12.1

Table 1. Continued

Question & Supporting Case Law	Yes	No	I Don't Know
7. Does the First Amendment right to free speech entitle teachers to teach creationism in the science classes of public schools? (Webster v. New Lenox School District #122, 917 F 2d 1004 [7th Cir. 1990]; Bishop v. Aronov, 926 F2d 1066,1077 [11th Cir. 1991]; Hellend v. South Bend Community School Corporation, 93 F3d 327 [7th Cir. 1996], cert. denied, 519 U.S. 1092 [1997])	8.7	72.5*	18.8
8. Has the court determined that creation science has no scientific merit? (McLean v. Arkansas, Board of Education, 529 F Supp. 1255 [E.D. Ark 1982])	34.3*	11.1	54.6
9. Students, their parents, school administrators, and other local residents all want a teacher to teach evolution and creationism in her science class. These are the people whose taxes pay the teacher's salary and support the school. If these people want the teacher to teach evolution and creationism, can the teacher teach them both? (McLean v. Arkansas Board of Education, 529 F Supp. 1255 [E.D. Ark 1982]; Edwards v. Aguillard, 482 U.S. 578 [1987])	15.5	59.4*	25.1
10. Can a school district force a teacher to stop teaching creationism? (Webster v. New Lenox School District #122, 917 F2d 1004 [7th Cir. 1990])	68.1*	3.9	28.0
11. Can a school require that a teacher teach evolution? (Peloza v. Capistrano Unified School District, 37 F3d 517 [9th Cir. 1994])	85.4*	1.0	13.7
12. Has the U.S. Supreme Court endorsed the teaching of "evidence against evolution"? (Edwards v. Aguillard, 482 U.S. 578 [1987]; the minority opinion mentions "whatever scientific evidence there may be against evolution")	1.4	42.5*	56.0
13. Does a science teacher's right to free speech entitle him or her to teach "evidence against evolution"? (LeVake v. independent School District #656, 625 N.W. 2d 502 [MN Ct. of Appeal 2000], cert. denied, 534 U.S. 1081 [2002])	10.2	62.6*	27.2
14. Can science teachers be required by school administrators to read aloud a disclaimer saying that their teaching of evolution is not meant to dissuade students from accepting the biblical version of creation? (Freiler v. Tangipahoa Parish Board of Education, 185 F3d 337 [5th Cir. 1999], cert. denied, 530 U.S. 1251 [2000])	25.6	37.2*	37.2
15. Can science teachers teach creationism if their school district adopts a course textbook that promotes creationism? (Hendren v. Campbell, Superior Court No. 5, Marion County, Indiana, 14 April 1977)	22.7	38.2*	39.1
16. Is evolution a religion? (Peloza v. Capistrano Unified School District, 37 F3d 517 [9th Cir. 1994])	1.9	96.1*	1.9
17. Does teaching evolution promote the religion of evolution and therefore violate the establishment clause of the Constitution? (Peloza v. Capistrano Unified School District, 37 F3d 517 [9th Cir. 1994])	1.4	91.3*	7.2
18. Did the Scopes trial strike down the laws that banned the teaching of human evolution? (Scopes v. The State of Tennessee, 289 S.W. 363 [Tenn. 1927])	20.4	35.9*	43.7
19. At the Scopes trial, was Scopes convicted? (State of Tennessee v. John Thomas Scopes, Nos. 5231, 5232 [Tenn. 1925])	38.2*	15.5	46.4
20. Is teaching intelligent design unconstitutional? (Kitzmiller v. Dover Area School District, 400 F. Supp. 2d 707 [M.D. Pa. 2005])	26.6*	31.4	42.0

Table 2. Teaching level and understanding of evolution-related laws.

Teaching Level	Mean	Min.	Max.	SD	*n*
Elementary	9.18	0	16	4.35	34
Middle/junior high	11.59	0	20	5.00	34
High/senior high	13.10	2	20	4.24	131

Table 3. Teaching experience and understanding of evolution-related laws.

Teaching Experience	Mean	Min.	Max.	SD	*n*
≤2 years	8.89	2	14	3.66	9
3–5 years	11.38	2	20	3.87	34
6–10 years	11.75	0	20	5.56	40
11–15 years	12.88	4	20	3.80	41
16–20 years	13.00	2	20	4.70	32
21–25 years	13.11	2	20	4.70	19
26–30 years	11.63	6	17	3.86	8
≥31 years	12.44	3	20	4.61	16

Table 4. Time devoted to teaching evolution and understanding of evolution-related laws.

Time Devoted to Evolution	Mean	Min.	Max.	SD	*n*
None	7.29	0	16	5.18	17
≤1 hour	10.71	7	14	2.70	7
2–4 hours	9.67	4	15	3.34	12
5–8 hours	11.80	5	17	3.65	15
9–12 hours	11.19	2	19	4.52	27
13–16 hours	12.58	3	20	3.63	36
≥17 hours	13.79	2	20	4.61	79

convicted (question 19), and if teaching intelligent design is unconstitutional (question 20).

There were differences in mean total scores on the legal questions among the three teaching levels surveyed (Table 2). A Kruskal-Wallis *H*-test showed that there was a significant difference in scores between teachers at the different levels (χ^2 = 15.803, df = 2, P = 0.000), with a mean rank score of 66.31 for elementary teachers, 95.51 for middle/junior high teachers, and 109.91 for high/senior high teachers. The mean number of correct responses was 9.18 among elementary teachers, 11.59 among middle school teachers, and 13.10 among high school teachers.

Overall, the mean total scores on the legal questions do not indicate a monotonically increasing trend based on years of teaching experience (Table 3). A Kruskal-Wallis *H*-test showed that there was a nonsignificant difference in scores between the different levels of teaching experience (χ^2 = 10.183, df = 7, P = 0.178), with a mean rank score of 58.22 for those with ≤2 years of experience, 86.32 for those with 3–5 years, 98.14 for those with 6–10 years, 108.76 for those with 11–15 years, 110.27 for those with 16–20 years, 115.03 for those with 21–25 years, 91.50 for those with 26–30 years, and 100.66 for those with ≥31 years. However, those with ≤2 years of teaching experience scored the lowest (mean = 8.89), and those with 3–5 years of teaching experience scored second-lowest (mean = 11.38).

There was a general trend of increased understanding of evolution-related laws with classroom time per class semester devoted to teaching evolution (Table 4). A Kruskal-Wallis *H*-test showed that there was a significant difference in scores between the different amounts of time devoted to teaching evolution (χ^2 = 27.922, df = 6, P = 0.000), with a mean rank score of 49.29 for those not devoting any time to teaching evolution, 75.57 for those devoting ≤1 hour, 64.67 for those devoting 2–4 hours, 92.97 for those devoting 5–8 hours, 86.35 for those devoting 9–12 hours, 103.17 for those devoting 13–16 hours, and 115.67 for those devoting ≥17 hours. Those teachers who devote no time to teaching evolution had the lowest mean score on the legal questions (7.29), and those who devote ≥17 hours of instructional time to evolution had the highest mean score on the legal questions (13.79).

○ Discussion

To our knowledge, this survey is the largest and most wide-ranging attempt to determine the extent to which K–12 public school teachers in the United States understand evolution-related case law. In addition, we sought to determine how much time teachers devote to teaching evolution. We are encouraged to find that the majority (60.2%) of teachers surveyed allot ≥13 hours per class semester to the teaching of evolution, especially given that 17.1% of those surveyed teach at the elementary level, where time devoted to teaching science in general is low. In 2018, classes in grades K–3 spent an average of 18 minutes on science instruction each day, and classes in grades 3–6 spent only 27 minutes a day on science (Banilower et al., 2018). In recent years, the number of hours devoted to teaching evolution has increased, which has been attributed to the increased emphasis in state standards (Borgerding, 2012). Berkman et al. (2008) found that nationally, high school biology teachers devote 13.7 hours per class semester to teaching evolution. A study of Ohio biology teachers indicated that they spent an average of 11.6 hours per class semester teaching evolution (Borgerding, 2012). Friedrichsen et al. (2016) provide a detailed overview of the class time that secondary science teachers in Missouri dedicated to 13 evolution-related topics, among which the most time was spent on natural selection.

Within our sample of teachers, only 8.7% avoid teaching evolution or teach alternatives to evolution. While Berkman et al. (2008) reported that 25% of their national sample devoted at least one or two hours to creationism or intelligent design, they noted that those numbers can be misleading because teachers may do so in order to criticize evolution or respond to student inquiries. Most of the teachers we surveyed indicated that evolution is a unifying topic throughout the course (48.3%) or that they teach evolution as a unit like any other topic (31.8%). Only 9.0% do not cover evolution at all, and 10.9% use phrases like "change over time" instead of evolution. Friedrichsen et al. (2016) found that 60% of secondary science teachers in Missouri teach evolution as a theme in their biology classes, while Berkman et al. (2008) found that nationally only 23% of teachers do so. Just how many teachers completely avoid evolution is not well established in the literature. Rutledge and Mitchell (2002) reported that 23–45% of the 552 Indiana public high school biology teachers they surveyed reported that they avoid or only briefly mention evolution in their biology classrooms. Among Canadian elementary school preservice teachers, almost a third had reservations about teaching evolution or planned to avoid it entirely (Asghar et al., 2007). The results of our survey suggest that this population of K–12 teachers from across the United States devote ample time to evolution and approach evolution either as a unifying theme throughout the course or as a stand-alone chapter like other course topics.

The primary focus of this study was to determine K–12 teachers' understanding of evolution-related laws. Taken as a whole, the responses indicate that a majority of the teachers surveyed possess a sufficient understanding of legal issues but lack sufficient understanding of the more nuanced aspects of evolution case law. When asked if it is still a crime to teach evolution anywhere in the United States today, 51.2% indicated they did not know and only 35.3% correctly responded that it is not. The survey results indicate that 54.6% of teachers did not know if the court determined that creation science has no scientific merit, while 34.3% responded correctly to the question. Only 26.6% of teachers correctly responded that teaching intelligent design is unconstitutional, while 42.0% stated they did not know.

The addition of the option "I don't know" is informative in that it may mean just that. These teachers do not know enough about the topic to confidently respond to legal questions referring to past court cases. For several of the questions, a high percentage of teachers chose "I don't know." Rather than guessing the answer, the teachers may have felt more confident simply stating that they did not know the answer.

These results indicate that greater emphasis on the legal aspects of teaching evolution is needed, both in K–12 teacher preparation programs and in ongoing professional development or graduate-level science education courses for inservice teachers. Science teacher education programs should consider the legal imperative of evolution instruction and assist teachers in moving beyond their comfort zones (Hall & Woika, 2018). We have produced some resources (Hermann, 2013, 2017; Shane et al., 2016, 2020) that science teacher educators can use to help prepare K–12 public school teachers to teach evolution in a manner consistent with the law. These readings provide an overview of the legal challenges to the teaching of evolution in public schools. Additionally, a recent study suggests that engaging students with direct readings of court cases can result in a shift in preservice teachers' views about teaching potentially unconstitutional alternatives (Vaughn & Robbins, 2017).

Vaughn and Robbins (2017) provide some strategies for teaching about evolution and the law that have implications for students' attitudes and understanding about evolution. Though their work was done with preservice teachers, the activities can be implemented with little modification for public school students as well. They required their students to write a three- to five-page paper about the legal and philosophical basis of teaching evolution in public school classrooms. Students read Supreme Court decisions (*Epperson v. Arkansas*, 1968; *McLean v. Arkansas Board of Education*, 1982; *Edwards v. Aguillard*, 1987; *Peloza v. Capistrano School District*, 1994; *Kitzmiller et al. v. Dover*, 2005), along with readings from books, magazines, peer-reviewed papers, and other sources. The students also read statements from religious organizations endorsing evolution (see Sager, 2008) and from religious scientists discussing how they reconcile their beliefs with their work. Perhaps the most challenging activity to implement would be to provide guest lectures by teachers of theology and philosophy; in the study these lectures were designed to speak about the different benefits and purposes of myth and science, truth and fact. Vaughn and Robbins (2017) found that when the preservice teachers were required to read and write about Supreme Court cases, their opinions shifted significantly. Support for teaching intelligent design and creationism declined from 26% to 11.5%. The authors found that only when their students were given the writing assignment described above, along with readings and analysis of specific classroom challenges, did a large majority of them end up supporting the teaching of evolution.

○ Conclusions

Our results provide insight into the current understanding of evolution-related case law among this sample of K–12 public school teachers from across the United States. The teachers surveyed generally maintain a sufficient understanding of legal cases surrounding the teaching of evolution, but there are some alarming instances of teachers not fully understanding information that should be more widely and deeply understood among science teachers. Knowing what legally can and cannot be done when teaching evolution can inform teachers' practice and help them navigate conversations with students either individually or in groups. All K–12 teachers across the nation should know that they may not teach creation science, intelligent design, or other forms of creationism – neither alone, nor in the interest of equal time, nor under the guise of evidence against evolution. Moreover, school district administrators must know that they can prohibit a teacher from teaching alternatives to evolution, and that they can require a science teacher to teach evolution. While science educators may believe that these facts are widely known by those who teach science in the United States, the results of this survey suggest that additional preservice and inservice training is required to ensure that all K–12 public school teachers in the United States are aware of and compliant with evolution-related laws.

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RESEARCH ON LEARNING

Differential Impacts of Religious Cultural Competence on Students' Perceived Conflict with Evolution at an Evangelical University

M. ELIZABETH BARNES, RUTH WERNER, SARA E. BROWNELL

Abstract

Evolution remains a controversial issue in the United States, particularly for evangelical Christians, who as a group have been a key player in anti-evolution education legislation. Religious cultural competence can be effective in decreasing undergraduate biology students' perceived conflict between religion and evolution. However, the impact on student populations who are particularly resistant to evolution is unknown. We explored the efficacy of culturally competent evolution education practices adapted for biology students in a genetics course at an evangelical Christian university. This included the presence of an instructor as a religious scientist role model who accepts evolution, and the use of the book The Language of God. *We explored how this curriculum affected students' conceptions of religion and evolution using pre- and post-surveys. We found a differential impact of the curriculum: 31% of the students who indicated that there was a conflict between their religious beliefs and evolution changed their conceptions to be more in line with scientific evidence, but the remaining 69% did not. We describe reasons why, including students' perceptions of* The Language of God. *This research indicates the challenges of implementing culturally competent evolution education for evangelical students, given their strong commitment to biblical literalism and their lower likelihood of being convinced by scientific evidence for evolution.*

Key Words: *evolution; nature of science; creationism; evangelical; Christianity; undergraduate.*

○ Introduction

Evolution is foundational to biology (AAAS, 2011), but many individuals struggle with accepting evolution because of their religious beliefs and/or cultures (Rissler et al., 2014; Barnes et al., 2019). Polls show that evangelical Christians have some of the lowest rates of acceptance of evolution, with only 24% of respondents agreeing that evolution is the best explanation for the origins of human life on Earth (Pew Research Center, 2009a). Features of evangelicalism known to promote an anti-evolution stance are a tendency toward a literal interpretation of the Bible, a reinforcement of anti-evolution attitudes by some leaders of evangelical churches (Numbers, 2006), and a long history of political and legislative attempts to remove evolution from the science curriculum (Pew Research Center, 2009b; National Center for Science Education, 2019). Thus, teaching evolution effectively to evangelical students will be important for improving attitudes toward evolution and for preventing future political and legislative attempts to diminish the quality and presence of evolution education in science curricula.

Religious cultural competence has been suggested as a way to implement more effective evolution instruction by attending to students' religious cultures in the context of learning evolution (Barnes & Brownell, 2017). This type of instruction includes a suite of practices that can help religious students feel less conflict with their religious identity when they are learning evolution. These practices can include providing religious role models who accept evolution (Holt et al., 2018), teaching that science is agnostic with respect to a God, and highlighting that evolution and religion can be compatible rather than contradictory (Wiles & Alters, 2011).

Despite the promise of using religious cultural competence for more effective evolution education, there is very little research on the effect of culturally competent evolution teaching practices on evangelical Christian students. Here, we explore the impact of a culturally competent curriculum that was developed for evangelical students in an upper-level genetics course at an evangelical Christian university using a pre- and post-instruction study design.

○ Methods

The Study Site: An Evangelical Christian University

The site for the study was a private, nondenominational, evangelical Christian university in the Midwest. The university's mission statement is consistent with definitions of evangelicalism and states that Christ-centered education is its top priority; all students and instructors must agree to adhere to these ideals. The university requires all students to complete 30 credits in theological studies, and the professor of the genetics course in this study confirmed

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that the university culture includes various expressions of evangelical Christianity, but tends to be theologically conservative. The university does not make an explicit statement on evolution, but the professor described an inherent bias against evolutionary science on the part of many students and employees, making this a unique context to study the impact of evolution education on Christian students.

The Biology Curriculum

Biology students at this university take 55 credits of science courses for their degree. Students must take three introductory biology courses before taking genetics to obtain their degree. During our study, in the first introductory biology course, the instructor taught evolution and revealed himself to students as a special creationist who does not accept macroevolution. In the second course, the instructor did not discuss religion and evolution. In the third course, the instructor taught about evolution and revealed that he accepts evolution.

Genetics Course with Religious Cultural Competence for an Evangelical Christian Population

In the 16-week upper-level genetics course, taught by a single instructor, students learned about the structure and function of DNA; the processes of DNA replication, transcription, and translation; and the principles of inheritance, regulation of gene expression, and molecular evolution. Students met for 65-minute sessions three times a week for the lecture portion of the class, and once a week for 2.5 hours for the lab portion. The course used lecture, group problem solving, and hands-on activities.

Below, to describe how the instruction aligned with religious cultural competence, we italicize components of instruction that specifically aligned with the components of the Religious Cultural Competence in Evolution Education (ReCCEE) framework outlined in Barnes and Brownell (2017). The instructor of the genetics course, who accepts evolution, told students about this personal view and thus served as an evangelical scientist *role model* who accepts evolution. Further, the instructor *acknowledged* potential conflict while maintaining a respectful disposition with all students regarding different views on evolution. The instructor also had students *discuss and explore* their personal views on evolution through discussion boards and reflection essays.

Students were assigned to read *The Language of God* by Francis Collins (2006). This book was chosen because it was designed to help evangelicals reconcile faith and evolution. Collins is the current director of the National Institutes of Health, former director of the Human Genome Project, and an evangelical Christian. The book describes the *bounded nature of science*, specifically that science does not test for the existence of God and is not atheistic. Collins also describes a *spectrum of viewpoints* on the relationship between religion and evolution, from conflict to compatibility. Together, these components show evangelicals that there is *potential compatibility* between their religion and their acceptance of evolution.

Instruments

Acceptance of common ancestry. To determine students' views of religion and evolution before and after the genetics course, we used a survey developed by Yasri and Mancy (2016). Students chose from the options shown in Table 1 both before and after evolution instruction. We categorize Literal, Progressive, Genera, and Human Creationism as in direct conflict with scientific evidence; and Theistic, Deistic, Agnostic, and Atheistic Evolution as not necessarily in conflict with scientific evidence (Figure 1).

Table 1. Before and after the genetics course, students chose from different views of the relationship between religion and evolution to indicate which was closest to their personal view.

Views in Direct Conflict with Scientific Evidence	
Literal Creationism	All forms of life were first brought into being at the same time by a deity, in more or less their present form.
Progressive Creationism	All forms of life were gradually created over time by a deity, in more or less their present form.
Genera Creationism	Some forms of life evolved from earlier forms created by a deity, but higher taxonomic groups such as reptiles, birds, and mammals were created in more or less their present form.
Human Creationism	Some forms of life evolved from earlier forms created by a deity, but human beings were created in more or less their present form.
Views Not Necessarily in Direct Conflict with Scientific Evidence	
Theistic Evolution	All forms of life evolved from earlier forms, but a deity intervenes from time to time to shape or override the evolutionary processes.
Deistic Evolution	All forms of life evolved from earlier forms, but life and evolution were first set in motion by a deity and then left running without any additional intervention.
Agnostic Evolution	Life emerged from nonliving particles and then all current forms evolved from these earlier forms. A deity may exist; however, this is out of the scope of evolutionary theory.
Atheistic Evolution	Life emerged from nonliving particles and then all current forms evolved from these earlier forms. No deity has ever played any role in the evolution of life on Earth.

Open-ended student responses on views of evolution and final written reflection. To further explore students' perceived conflicts between their religious beliefs and evolution before and after the genetics course, we asked them to respond to one open-ended question (prompt: "Do you see a conflict between evolution and your personal beliefs? Yes/No/Unsure. Explain why you gave the answer you did. Why do you feel there is a conflict or why don't you feel there is a conflict or why are you unsure?"). We also analyzed students' final essay after they had read the entire book (prompt: "How has *The Language of God* challenged or advanced your thinking about the integration of science and faith?").

Analyses

We examined whether students' responses to the "acceptance of common ancestry" survey changed from pre- to post-course. Figure 2 illustrates how we ranked each option in terms of level of conflict with acceptance of evolution. Students' choices were triangulated with their written reasoning for why they did, did not, or were unsure if they perceive conflict between their beliefs and evolution. The final reflection essays were analyzed to explore how students' conceptions of evolution changed in response to *The Language of God*. Qualitative data were analyzed using constant comparative methods to identify themes in student responses (Glaser & Strauss, 1967). A subset of data was initially coded together by three researchers to identify themes in student responses. Following the initial identification of these codes, the first author reviewed the data again and identified additional codes. Codes were then grouped into broader themes. The two other researchers reviewed the final themes to confirm agreement on all themes. All names are pseudonyms used to protect subject identity. The study was approved by the university's institutional review board.

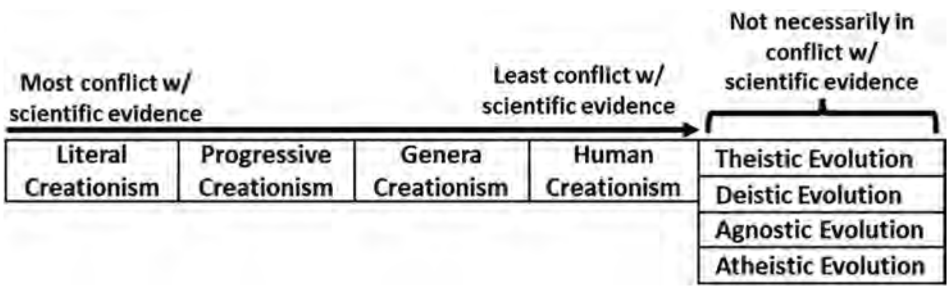

Figure 1. Ranking of positions on religion and evolution by level of conflict with evolution.

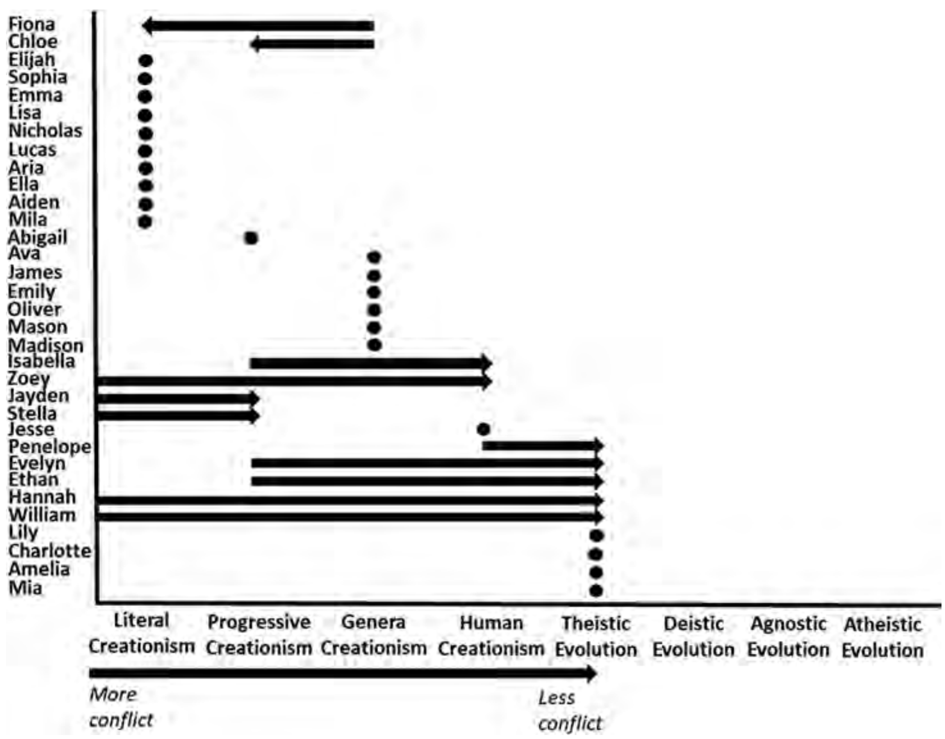

Figure 2. Students' personal views on religion and evolution before and after the genetics course. The head of the arrow represents the view that students changed to at the end of the course. Dots represent students who did not change their views. No students chose Deistic, Agnostic, or Atheistic Evolution on either the pre- or post-survey, further illustrating the unique religiosity of this population.

○ Results

Participants

The study population consisted of 33 students in the upper-level genetics course, 32 of whom were biology majors; 33% were male and 67% were female. Twenty-four students identified as pre-health, three planned to go into conservation-related careers, four planned to go into research or academic careers, and two had unknown career aspirations. All students identified as Christian.

Pre-course & Post-course Acceptance of Common Ancestry

At the beginning of the course, 19 of the 33 students (58%) did not accept common ancestry in any form; 10 (30%) accepted only some aspects of common ancestry; and four (12%) fully accepted common ancestry in the form of Theistic Evolution. No students chose Deistic, Agnostic, or Atheistic Evolution.

At the end of the course, 15 of the 33 students (45%) did not accept common ancestry in any form. Nine of the 33 students (27%) accepted only some aspects of common ancestry, and another nine (27%) fully accepted common ancestry in the form of Theistic Evolution. Again, no students chose Deistic, Agnostic, or Atheistic Evolution.

Overall, among the students who did not already accept Theistic Evolution at the beginning of the course, 31% made a positive shift toward less conflict with evolution, 62% did not change, and 7% made a negative shift to more conflict. Figure 2 shows each individual student's pre- and post-instruction choices.

Qualitative Results

Through triangulation of closed-ended pre- and post-survey data, qualitative open-ended survey data, and written reflections, we identified four main qualitative categories of students based on the development of their views on evolution and religion over the genetics course. Each category is outlined below, and illustrative quotes from students are given in Tables 2 and 3.

Stayed with Theistic Evolutionism

Students in this category already accepted evolution at the start of the genetics course. Four students were in this category. These students chose Theistic Evolution on both the pre-survey and post-survey and did not indicate that the course had influenced their beliefs. For instance, in Mia's pre- and post-survey

Table 2. Examples of students' statements before and after the genetics course. These students either had already reconciled their religious beliefs with evolution before taking the course, made a positive shift toward less conflict, or became more uncertain of their special creationist beliefs.

Category	Before Genetics Course	After Genetics Course
Stayed with Theistic Evolutionism	Mia: "Many people I know think [evolution] is wrong, and if you have the slightest interest in evolution you are a bad Christian. I strongly disagree."	Mia: "I strongly believe that evolution was part of God's plan when he created."
Changed to Theistic Evolutionism	Penelope: "For the majority of evolution, there is no conflict. I believe in microevolution. I believe that there is evidence for some larger scale macroevolution. I don't think we can be certain about how long a "day" is in Genesis, and if we should take it as a literal day or a figurative day. I think of it more in a figurative stance. I still believe the days represent phases of creation, but not the literal 24-hour days. I don't think God would leave evidence when it wasn't true and even though evidence is often subjective, I do not believe it was initially meant to contradict religion."	Penelope: "I don't feel like there is a conflict between evolution and my personal beliefs. I don't think there could be. It is one of my fundamental beliefs that God would not lay false evidence into creation for us to find. If we are getting things wrong, then we are interpreting evidence wrong . . . nor do I believe that the evidence for evolution is coincidental . . . I think when you combine this information with the other evidence that scientists have found, I lean towards believing in an evolutionary process."
Became More Uncertain about Special Creationism	Elijah: "I know, based on my knowledge of biology, that cells cannot arise from non-cells. This rule, which science has never been able to break, limits the ability of evolution to account for life. Knowing this, I believe God must have been instrumental in creation . . . (but) my faith is not resting on an explanation for creation."	Elijah: "I was very surprised by how challenged I was feeling [by the book]. After Collins presented his evidence, like the chimp chromosomes or the AREs (Ancient Repetitive Elements), I couldn't seem to find a hole in this logic. After reading this book, I cannot say I am completely convinced of evolution's presence, but I am far more uncertain than I was at the beginning of the book. I haven't been convinced, but I can understand the opposite opinions."
	Stella: "Though there are many individuals who are proponents of theistic evolution, I have always found myself taking a more literal approach regarding the creation account. This may be due, in part, to a familiarity and comfort that comes along with the '7 day' creation story I have heard since being a young child in Sunday school. Yet, as the years have gone on and I have learned more about the spectrum of positions regarding creation, I still tend to cling to a more literal approach of the Scriptures. It seems to me that God created plant and animal, as well as male and female, as whole and complete."	Stella: "I believe that I am left with more questions than answers [after the course] . . . I am weighing the evidence for both sides with a critical eye and genuine heart. To be honest, I would say that I would tend to side with a more literal or progressive creation account. Maybe it is partially to do with the fact that this is the way I was raised; however, I have also found myself with more questions about my faith when contemplating theistic evolution. I do read Genesis as more of a narrative story, and struggle to take the accounts of Adam and Eve and the flood as only symbolic . . . though the genetic and scientific evidence does indeed seem to support evolutionary origins. . ."

Table 3. **Examples of students' statements before and after the genetics course. These students did not make a positive shift toward less conflict and did not become more uncertain of their special creationist beliefs.**

Category	Before Genetics Course	After Genetics Course
No Change (Wavered)	Sophia: "The mere probability of evolution occurring is so extraordinarily impossible. The more science classes I take, the more stupefied I am: all life is arranged perfectly all the way down to atomic detail. I don't have enough faith in random chance to believe evolution, while believing that an all-powerful deity brought about the world is much more plausible."	Sophia: "Reading this book was quite difficult in the beginning . . . The more I considered a theistic evolution perspective, the more I realized it was a much more founded theory than I had ever believed . . . After the first few chapters, I was almost converted to theistic evolution because I did not have answers or rebuttals to Collins' questions and facts. It took a few weeks of searching and analyzing my creationist views to come to peace about my own views. While I have concluded that I cannot accept Collins' viewpoint, my mind has been opened to new ideas and ways of thinking."
	Lisa: "There is a spectrum of belief between theistic evolution and literal creationism. I lean much farther towards the literal creation side of this spectrum. I believe that Adam and Eve were real individuals who existed at a defined point in time. I believe that approximately 6,000 years ago, there was a global flood that destroyed every living thing except for the people and animals aboard the ark built by Noah and his sons."	Lisa: "I will freely admit that the biological evidence for macroevolution presented was compelling . . . and yet, after having read and processed all of the arguments in the book, I still must fall back on the worldview that I had at the beginning of the semester. At the end of the day, I would far rather be a mediocre scientist who holds some antiquated scientific beliefs than be a cutting-edge scientist who is respected . . . but has squishy theological beliefs."
No Change (Did Not Waver)	Aria: "I disagree with evolution simply because I believe that science does not support evolution."	Aria: "I just do not think there is enough compelling evidence to support evolution."
	Oliver: "I would call myself an old earth creationist. To deny that the earth is old is to completely throw away science. I don't think that can be denied, but I can deny macroevolution."	Oliver: "I do believe in microevolution between species. That is observable science and can be observed happening today."
	James: "What I struggle with is how macroevolution changes an organism on a scale where not only the species changes, but also its genus and family . . . that is difficult to observe . . . so it makes it difficult to run experiments that follow the scientific process."	James: "After reading *The Language of God*, I have found that my beliefs have not really changed . . . I am one who looks at it from a microevolutionary perspective rather than macroevolutionary."

responses (Table 2), she indicated that she had already accepted evolution and did not experience a conflict. Their responses indicate that these students had already reconciled their religious beliefs with evolution before taking the genetics course.

Changed to Theistic Evolutionism

Students in this category changed from a special creationist belief to a belief in theistic evolution over the course. Five students were in this category. The open-ended responses on the pre-survey indicated that these students were questioning aspects of their creationist beliefs even before taking the genetics course. In their pre-course responses, many of these students questioned their literal interpretation of Genesis and wondered if their religious beliefs needed to conflict with evolution; in their post-course responses, they indicated that they perceived no conflict (Table 2). The course thus had a positive impact on the acceptance of evolution by these students who were already questioning their special creationist beliefs.

Became More Uncertain about Special Creationism

Students in this category started and ended the genetics course believing in some form of special creationism, but they became more uncertain about these beliefs over time. Seven students were in this category. Sometimes this uncertainty reflected a change in the students' beliefs about special creationism. For instance, although Zoey started and ended the course believing in a form of special creationism, she changed from believing in Literal Creationism to accepting all of evolution except for human evolution (Figure 2); previous studies have shown that human evolution is particularly challenging for students to accept (Barnes et al., 2019). Other students ended the course with the same creationist beliefs they had at the beginning of the course. However, in their post-survey responses, they indicated that they had become less confident about those beliefs. For instance, although Elijah chose Literal Creationism both pre- and post-course (Figure 2), he indicated that he was more uncertain of these beliefs than at the beginning of the course (Table 2).

Almost all of these students attributed their uncertainty to two factors. First, they were willing to admit that at least some of the evidence for evolution was compelling. Second, they said they were unsure if they had rejected evolution only because of the sociocultural norms established by their upbringing (see Stella's comment in Table 2).

These students' responses indicate that although it did not change their acceptance enough for them to choose Theistic Evolution on the evolution survey, the course did have a positive impact on their acceptance by making them more uncertain about their special creationist beliefs.

No Change

Students in this category showed no evidence of reducing their perceived conflict by the end of the semester. A subset of students in this category indicated in their post-course survey responses that during the course they had wavered about their creationist beliefs, but they ended the course with a confident belief in the same form of special creationism. Three students were in this subset. These students admitted that the evidence for evolution was compelling, but ultimately they still rejected evolution. Sophia illustrates this in her reflection on reading *The Language of God* (Table 3).

The reasons for their continued rejection of evolution, even in the face of evidence they found compelling, seemed to be that they valued evidence from religious texts more than they valued scientific evidence. These students said that even though the evidence for evolution was compelling, they were unwilling to sacrifice their literal interpretation of the Bible. Mainly, they saw sacrificing a literal interpretation of the Bible as undermining a staple of their religious beliefs, the story of Adam and Eve. Further, these students all ultimately said that their faith in religion is greater than their trust in science, so when the two conflict, they will always choose their faith (e.g., see Lisa's post-course statement in Table 3). These data illustrate that even when the evidence for evolution is compelling, it will not always be enough to change a student's mind about evolution if they ultimately place higher value on what they perceive to be evidence from religious texts.

Other students in the No Change category did not indicate that they had wavered at all during the semester. Fourteen students were in this subset. The main difference between these students and those who wavered was that these non-wavering students did not report ever finding the evidence for evolution compelling. When they discussed evidence for evolution in their responses, it was to refute the evidence. While all students who wavered admitted that their "faith was more important than evidence from science," most of these students did not make such a claim, because they maintained that their creationist beliefs were supported by the scientific evidence and that they had scientific questions that were not sufficiently answered by Collins's book or the genetics course (Table 3). Two students, Chloe and Fiona, chose special creationist views that were less compatible with evolution at the end of the course than at the beginning. Unfortunately, their open-ended responses did not provide information as to why they chose these views instead of their original special creationist views.

The most cited reason among these students that the evidence for evolution was not compelling was the thought that evolution cannot be observed. In fact, many students said that they accepted microevolution because it was observable but did not accept macroevolution (see James's statements in Table 3).

These data indicate that upper-level biology majors at this institution maintained misconceptions about evolution and the nature of science, and used these misconceptions to assert that scientific evidence supports special creationism and not evolution.

Student Reactions to *The Language of God*

Student reflections and surveys indicate that their reactions to reading *The Language of God* were primarily positive. In their survey responses, only three of the 33 students had exclusively negative reactions to the book; 20 had exclusively positive reactions; seven had both positive and negative reactions; and three did not say anything distinctively positive or negative about the book. Themes in the positive reactions include students' perception that the book encouraged self-reflection about their own views, forced them to think critically about evolution and faith, and made them more open to others' points of view. The students also discussed how they liked learning new evidence for evolution. The most-reported examples of scientific evidence from the book that the students found compelling were Collins's discussion of ancient repetitive elements and the ape chromosome fusion event that happened during the evolution of the human lineage. Additionally, students mentioned that they appreciated the arguments presented by Collins for a nonliteral interpretation of the Bible. One point that was mentioned repeatedly was Collins's discussion of how the Bible was "written for ancient people" before the scientific discoveries of the past few thousand years, and therefore the stories in the Bible were written in a way "that made sense to the people of Moses' time." Further, some students appreciated that Collins argued for compatibility between science and religion and that he was a good role model because he is a religious scientist who argues for both faith and science.

However, students also had several negative reactions to reading the book. The most frequent negative response was that students felt, at times, that Collins took an unnecessarily "harsh tone" against views that reject common ancestry and seemed to be "judgmental of students who are young-Earth creationists." These students felt as though Collins was not open enough to points of view other than his own. Several students brought up an excerpt in the book in which Collins says that "no serious biologist today doubts the theory of evolution to explain the marvelous complexity and diversity of life" (p. 99), and this seemed to be particularly offensive to some of the students who rejected common ancestry. These results are summarized in Table 4 with example quotes from students.

Table 4. Emergent themes from data regarding students' reactions to reading *The Language of God* (Collins, 2006).

Student Reactions	Example Statements	
Positive reactions		
Encouraged self-reflection	Charlotte: "Francis Collins' The Language of God has forced me to think beyond what I have in the past regarding . . . science and faith."	Olivia: "I felt like with every chapter I read, it challenged me to reflect on my own faith and look inside myself to see what I believed."
Became more open to others' points of view	Mia: "This book also made me more open-minded about other ideas and perspectives."	Ella: "I think (the book) has made me more open to at least listening to other theories about creation/evolution."
Learned new evidence for evolution	Evelyn: "Reading about the scientific evidence for evolution was eye-opening to me."	Ethan: "Through this book I became aware of strong evidence for evolution."
Learned new evidence for a nonliteral interpretation of the Bible	Zoey: "I now understand that some of the Bible may be a metaphor or meant in a slightly different way. For instance, yes God could have created the Earth in six 24-hour days if he wanted to, but he could have also used multiple years to complete his work."	Emily: "Prior to reading this book, I had always approached Genesis as a literal writing, but I can see how it is possible that the language used in Genesis was not meant to be a complete scientific account of creation. Rather, it could be more of a simplified explanation for creation that made sense to the people of Moses' time."
Collins taught compatibility between science and religion	Emily: "Often, as this book highlights, there is a misconception that scientists cannot also be Christians. It was encouraging to read about a man who is clearly a brilliant scientist but also a fearless lover of the Lord."	Mila: "I didn't even really know that there was such a large group of people who believed in God and evolution, I simply thought that the two are completely incompatible. However, since reading the book, I have learned that the two can in fact coexist."
Negative reactions		
Collins was too harsh toward special creationists	James: "I struggled with the language used by Collins . . . especially towards those who are young-Earth creationists. His language appeared almost hostile and judgmental, which I did not respect."	Ava: "This book was very challenging for me. I did not appreciate Collins' attitude throughout the book, which made it difficult for me to take him seriously."
Evidence for evolution is not compelling	Ava: "Collins did not present much evidence in favor of his position, which was frustrating to me."	Emma: "When reading about how certain genes in chimpanzees are also found in humans, I couldn't help but think that was just a coincidence."

○ Discussion

We found that a genetics course at an evangelical Christian university that incorporated religious cultural competence and *The Language of God* into its curriculum had a differential effect on students. We found that students who changed from rejecting to accepting common ancestry were questioning their special creationist beliefs at the beginning of the course. This supports the idea that changing from rejecting to accepting evolution is not an immediate event, but a process that takes time (Winslow et al., 2011). We also found that some students became more uncertain of their creationist beliefs over the semester. Although these students did not change their viewpoint by the end of the semester, they may have moved further on a path toward accepting evolution in future years.

We documented that students who either changed to accepting evolution or became more uncertain of creationist beliefs often cited that the evidence for evolution is compelling, whereas those who did not change at all also cited evidence in their reasoning but said the evidence was not sufficient. This calls into question whether or not evidence for evolution is generally sufficient for changing students' views on evolution. The only students who changed to accepting evolution or became more uncertain about their special creationist beliefs were ones who not only cited evidence for evolution, but also recognized that evolution could be compatible with their religious beliefs. Perhaps presenting evidence alone is an effective change agent only if there is no "identity barrier" present (Kahan & Stanovich, 2016).

Student reactions to *The Language of God* [1] indicated that using religious cultural competence effectively may depend on one's ability to maintain a perception of openness and respect for all beliefs. The most common negative reactions to the use of the book were specific passages in which Collins made remarks that were perceived as disrespectful, closed-minded, and too forceful. This is in line with our past research in which students said they decreased their perceived conflict between religion and evolution when the instructor communicated that they were respectful of student beliefs and would not force students to accept evolution (Truong et al., 2018). If an instructor incorporates some culturally competent practices (e.g., showing examples of religious biologists) but students perceive hostility, judgment, or intolerance of their own religious beliefs in certain statements by the instructor, the culturally competent practices may be less effective.

This research indicates that even conservative, evangelical college biology students, whom we would expect to be the most resistant to evolution, can change their minds in response to evolution education using religious cultural competence (Barnes & Brownell, 2017). The instruction in this course did not have as great an impact on changing students' perceptions of evolution as what has been reported previously (Barnes et al., 2017; Truong et al., 2018). However, those prior studies were done with first-semester biology students at a secular liberal university and did not measure students' change in acceptance of evolution, but only their views on whether evolution and religion could be compatible. In the present study, the students were advanced biology majors who had already been in college learning about evolution and religion for several semesters, so many of them had firm views coming into this upper-level class. Further, these evangelical students were especially resistant to evolution compared to students in our prior studies, with the majority of students choosing a young-Earth creationist view at the beginning of the course. Therefore, although the impact on students is smaller in this context than in other studies, the success we did see here is encouraging – it indicates that instruction can have an impact on these particularly resistant students. However, the limited effect also indicates that more research is needed to increase the efficacy of these interventions among conservative evangelical Christian students.

Limitations

This study looked at one population of students at one university, and the results are not intended to be generalized to other populations. Additional research should explore other populations of evangelical biology students to see if similar results are obtained. Further, while the survey used in this study was chosen because of its prior use in the literature, it may not have captured nuances of students' views due to differing definitions of theistic evolution.

Conclusion

In this study, we found that using a religious scientist role model instructor who accepted evolution and the use of the book *The Language of God* in the context of a genetics course at an evangelical university decreased the perceived conflict with evolution for nine out of 28 students who did not already fully accept evolution, but did not have an impact on the other 19 students. This research indicates that evangelical Christian students may have a particularly difficult time decreasing their perceived conflict with evolution. Culturally competent instruction may be effective for some evangelical students, but future research could explore how to increase its efficacy among this population of students.

Notes

1. Given the religious nature of *The Language of God*, assigning this book for students to read in a biology course at a public university would not be appropriate. However, the book could serve as a potential resource for public college instructors to (1) learn about the views their evangelical Christian students may have and how these students might reconcile their religious beliefs and evolution and (2) recommend the book to evangelical Christian students who may be struggling with accepting evolution. However, our results indicate that it will not be effective for all students, particularly among students who are unwilling to question a literal interpretation of the Bible.

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ABT AUTHORS & PHOTOGRAPHERS Guidelines

We encourage our readers, biologists with teaching interests, and biology educators in general, to write for *The American Biology Teacher*. This peer-reviewed journal includes articles for teachers at every level, with a special focus on high school and post-secondary biology instruction.

Revised August 2018

General Categories

The general categories of articles are:

Feature Article (up to 4000 words) are those of general interest to readers of *ABT*. Consider the following examples of content that would be suitable for the feature article category:

a. Research on teaching alternatives, including evaluation of a new method, cooperative learning, concept maps, learning contracts, investigative experiences, educational technology, simulations and games, and biology and life science education standards

b. Social and ethical implications of biology and how to teach such issues as genetic engineering, energy production, pollution, agriculture, population, health care, nutrition, sexuality and gender, and drugs

c. Reviews and updates of recent advances in the life sciences in the form of an "Instant Update" that brings readers up-to-date in a specific area

d. Imaginative views of the future of biology education and suggestions for adjusting to changes in schools, classrooms, and students

e. Other timely, relevant and interesting content like discussions of the role of the Next Generation Science Standards in biology teaching, considerations of the history of biology with implications for the classroom, considerations of the continuum of biology instruction from K-12 to post-secondary teaching environments, or contributions that consider the likely/ideal future of science and biology instruction.

Research on Learning (up to 4000 words) includes reports of original research on innovative teaching strategies, learning methods, or curriculum comparisons. Studies should be based on sound research questions, hypotheses, discussion of appropriate design and procedures, data and analysis, discussion on study limitations, and recommendations for improved learning.

Inquiry and Investigations (up to 3000 words) is the section of *ABT* that features discussion of innovative laboratory and field-based strategies. Strategies in this section should be original, engaging, focused at a particular grade/age level of student, and include all necessary instructions, materials list, worksheets and assessment tools, practical, and related to either a particular program such as AP and/or linked to standards like NGSS. The most appropriate contributions in this category are laboratory experiences that engage students in inquiry.

Tips, Tricks and Techniques (up to 1500 words but may be much shorter) features a range of suggestions useful for teachers including laboratory, field and classroom activities, motivational strategies to assist students in learning specific concepts, modifications of traditional activities, new ways to prepare some aspect of laboratory instruction, etc.

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- Manuscripts must be submitted as Word or WordPerfect files.
- Format manuscripts for 8.5 × 11-inch paper, 12-point font, double-spaced throughout, including tables, figure legends, and references.
- Please place figures (including photos) and tables where they are first cited in the text along with appropriate labels. Make sure to include figure and table citations in the text, as it is not always obvious where they should be placed. At the time of initial submission, figures, tables and images should be low resolution so that the final file size remains manageable.
- If your article is accepted, the editors will require that figures be submitted as figure files in higher resolution form. See below for file format and resolution requirements.
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- Authors are encouraged to submit multimedia files to accompany their articles. Acceptable file formats include MP3, AVI, MOV, WMV, and FLV.

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continued

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INQUIRY & INVESTIGATION

The Natural Selection Game: Incorporating Active Learning in Evolution Curricula for General Biology

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Abstract

Teaching evolution in high school and in entry-level college courses can be challenging due to the inherent misinformation, misunderstanding, and biases with which students approach the topic. In this setting, it is critical to both teach the basic concepts and address common student misconceptions about evolution. We present two paired activities that allow students to (1) explore the processes of natural selection in a direct and experiential way and (2) address common misconceptions in evolutionary theory. The first activity, the "Natural Selection Game," has students simulate a bird population and experience shifts in phenotype frequency as a result of selective pressures. Following the end of the game, students discuss the outcomes and connect them to real-life examples. The second activity encourages students to actively research common misconceptions with the use of personal technology in order to distinguish between scientifically supported data and poor information online. Both activities can be incorporated in high school and university-level general biology curricula. They will allow students to connect their firsthand experiences to lecture-based instruction and, as a result, develop a stronger understanding of the mechanisms of evolution.

Key Words: *evolution; natural selection; active learning; biology curriculum; pedagogy; hands-on game.*

○ Introduction

For science educators tasked with teaching evolution at the high school or university level, presenting evolution as a coherent and unifying principle of biology has faced a wide array of challenges and missteps over past decades (reviewed in Alters & Nelson, 2002; Rutledge & Mitchell, 2002; Friedrichsen et al., 2016). Traditional pedagogical approaches have involved instructor-centered teaching in which information is presented to students with the expectation that it will simply be transferred and in which misconceptions about topics are often left unaddressed (Alters & Nelson, 2002). This approach favors students who can figure out how to retain the information necessary while leaving the rest to flounder. The advent of the *Next Generation Science Standards* (NGSS) in Science, Technology, Engineering, and Math (STEM) has tackled this issue by sparking a nationwide movement toward more student-centered pedagogical approaches (Achieve Inc., 2013). With this new trend, many teachers and institutes have strived to incorporate more active-learning techniques in classroom curricula (Grooms et al., 2015; Friedrichsen et al., 2016; Odom et al., 2017; Puttick & Drayton, 2017). As a result, much progress has been made toward reforming teaching practices in biology through the development and publication of active-learning strategies for teaching core concepts (see, e.g., Lauren et al., 2016; Odom et al., 2017; Rowland et al., 2017; Kane et al., 2018). We hereby contribute to these strategies with a fun and engaging improvement to a classic activity for teaching natural selection.

It can often be difficult for students to fully grasp the complex mechanisms of evolution, as it requires the ability to think scientifically (Crawford et al., 2005). Students typically view academic knowledge dichotomously as either right or wrong, and they tend to passively accept information rather than analyze evidence that contradicts misconceptions (Alters & Nelson, 2002). In order to encourage critical thinking, instructors should engage students in activities that lead them to discover facts on their own, rather than provide the facts for them (Snyder & Snyder, 2008). The challenges of teaching evolution can be particularly severe in nonmajors and general biology courses in which students have limited background in necessary biological concepts, and where time allocated to the discussion of evolution may be limited. However, one study has shown that even students who majored in biology scored only slightly better than nonmajors on the topics of ecology and evolutionary biology (Sundberg & Dini, 1993).

Further exacerbating the challenge of teaching evolution are opposing religious views and religious organizations that have actively stigmatized the topic for students in the United States and abroad (Lawson & Weser, 1990; Alters & Alters, 2001; Antolin & Herbers, 2001; Tidon & Lewontin, 2004). The most recent Pew Research Center report on the issue indicated that, on average, 31% of Americans did not believe that humans evolved over time,

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and 29% did not believe that scientists agreed on evolution (Funk & Rainie, 2015). Furthermore, surveys of student conceptions of evolution have revealed the persistence of recurring misconceptions, which pose a major impediment to grasping evolutionary theory if left unaddressed in the classroom (Bishop & Anderson, 1990; Demastes et al., 1995; Alters & Nelson, 2002).

Ultimately, the solution to improving public understanding of evolution converges on teaching approaches. Conveying a solid understanding of the mechanisms of complex concepts in a manner that incorporates team-based learning and simulation models has been shown to be successful in the classroom setting (Zacharia, 2005; Grisé et al., 2011). This method allows students to explore and discover concepts through their experience, and positions them to better understand the associated facts presented by the instructor as a follow-up. Furthermore, having students address common misconceptions in an active manner is vital to guiding them toward a more complete and informed position when teaching valuable and potentially contentious topics (Nelson, 2008). This strategy encourages students to be open to exploring misinformation that may already be part of their personal understanding of the topic, and helps instructors facilitate the learning of potentially sensitive topics without outright student rejection (Smith, 1994; Nelson, 2008). For these reasons combined, it is imperative to conceptualize and present innovative and novel learning strategies that are effective in conveying a comprehensive understanding of evolution, as we have done here.

○ Examples of Natural Selection

Classic examples of natural selection often involve populations of organisms that experience phenotypic variation shifts toward one end of an extreme (i.e., directional selection) as a result of an environmental change (Grant & Grant, 2002; Brodie et al., 2005; Cook & Saccheri, 2013; Mills et al., 2018). Examples of natural selection that encompass both the microevolutionary and macroevolutionary scales are ideal for incorporating into evolution curricula. For example, Hoekstra et al. (2006) demonstrated that a single nucleotide mutation in the melanocortin-1 receptor gene (*Mc1r*) of beach mice was responsible for a malfunction of the melanocortin-1 protein, which results in lighter fur pigmentation. The codominant nature of both mutated and wild-type *Mc1r* alleles resulted in a spectrum of fur color, and the prevalence of a specific fur color in an individual population reflected habitat substrate (Mullen et al., 2009). Allelic frequencies of fur colors that matched the habitat's substrate were higher than those that did not, because individuals with fur colors that provided the best camouflage were more likely to survive against visual predators (Hoekstra et al., 2004; Mullen & Hoekstra, 2008). A similar example of natural selection involves the recent rapid evolution of mammals that undergo a seasonal fur color molt from summer brown to winter white (Jones et al., 2018; Mills et al., 2018). In this case, shortening winter periods have caused lowered fitness for winter white individuals that inhabit increasingly snowless environments as a result of anthropogenic climate change (Mills et al., 2018). These examples demonstrate how environmental changes can cause shifts in allele frequencies based on individuals' ability to avoid predation. Alternatively, the evolution of Darwin's finches presents classic examples of how environmental changes can cause shifts in population allele frequencies based on individuals' abilities to exploit food resources (Grant & Grant, 2002). For example, a reduction in the number of seed-producing plants resulting from a severe drought in 2004–2005 caused medium ground finches (*Geospiza fortis*) with larger beaks to die off, while individuals with smaller beaks survived because they were able to exploit a wider variety of seeds (Lamichhaney et al., 2016). The genetic source of Darwin's finch beak size was recently traced to the *HMGA2* gene, which occurs as a codominant allele, although the exact pathway by which the gene controls beak size has yet to be elucidated (Lamichhaney et al., 2016). These examples are just a few of the many real-world cases of natural selection that can be used to relate to the experiences the students gain after participating in our natural selection simulation. The "Natural Selection Game" we present here can be directly related to the Darwin's finch system. This activity builds on a classic active-learning strategy that exists in various forms of teaching resources (Walker, 2003; Roehl et al., 2013). Although this activity is not novel, it improves on previous models by incorporating a genetic inheritance component and addressing parasite load to more accurately simulate natural selection.

○ Game Overview

In the Natural Selection Game, students simulate a population of birds with two beak shapes. Their beaks determine how efficient they are at collecting their primary food source, which consists of two types of insects. Throughout the game, students compete with each other over food resources, and as a result we see the phenotypic variation of the population shift toward one end of the spectrum or the other, depending on what "insect" is most prevalent as their food source. Following the game, students discuss the connections between what they experienced in the game and the mechanisms of evolution, through a guided series of questions and a presentation of real-life examples from the instructor.

We suggest having students participate in the game, discuss the results through a series of questions, relate them to real-world examples such as those addressed above, and then address misconceptions following the game. This arrangement allows students to first explore and experience the principles of natural selection, then connect their experiences from the simulation with the proper vocabulary and facts for these processes. Following these activities, students will be ready to actively address misconceptions about evolution through the group activity we describe following the Natural Selection Game.

The objective of the game is to immerse students in a simulation that allows them to experience natural selection by actively participating in the "struggle to survive." The game is designed to fit into a general biology curriculum as the introductory segment of a lecture series that introduces key concepts and misconceptions of evolution and discusses the mechanisms of natural selection and speciation (e.g., gene flow, vicariance). It is meant to follow lectures covering genetics. The goal of the game is to guide students to discover the concepts of evolution on their own through an active learning experience. An outline of the game is presented in Table 1. This activity meets *Next Generation Science Standards* MS-LS2-1, MS-LS2-4, MS-LS2-5, MS-LS4-4, MS-LS4-6, HS-LS4-2, and HS-LS4-5.

Table 1. A general overview of game play for the "Natural Selection Game."

Step 1	Students are assigned one of two beak phenotypes (spoon or chopsticks) and the associated genotype (two beak shape alleles).
Step 2	Students use their "beaks" to feed on two types of "insects," one of which is more plentiful than the other.
Step 3	Students who feed on enough "insects" survive to reproduction and pair up with another successful student to tag in two additional students who randomly receive one beak allele from each "parent" genotype.
Step 4	The game continues for several rounds and students with the most efficient beak phenotype "reproduce" more frequently.
Step 5	The game is interrupted by a simulated natural disaster, which shifts the food availability.
Step 6	Students resume the game and should find that the alternate beak phenotype becomes more efficient, and the population shifts toward the alternate beak phenotype.
Step 7	Students break up into groups and are tasked with answering questions that help connect their experiences in the game with real-world parallels.

○ Materials

- Several packs of gummy worms (amount will vary based on number of students participating)
- Several packs of low-friction, relatively round candy (amount will vary based on number of students participating; it is important that the candy be easier to pick up with a spoon than with chopsticks)
- A stack of clean paper
- A handful of coins (~20 coins should be more than sufficient)
- ~30 pairs of chopsticks (amount will vary based on number of students participating)
- ~30 spoons (amount will vary based on number of students participating)
- Access to one or more large tables, around which students can gather

○ Game Setup

On a large table, lay out clean paper to cover the center of the table (Figure 1A). Around the edge of the table, set up as many individual sheets of paper as can fit (Figure 1A). The paper covering the center of the table represents the substrate in which the food source (i.e., candy) of the birds is found. The amount of candy placed on the table will depend on the number of students participating in the game and should be estimated by the instructor. The two types of candy represent different types of insects that are available as a food source for the birds in this given hypothetical population. Gummy worms represent worms, while round candy represents beetles. For the first few rounds of the game, worms are the dominant food source and therefore more gummy worms should be made available on the table than round candy. Each student in the first round of the game receives an individual sheet of paper that represents their stomach content and that indicates their beak genotype. Before the start of the class, pre-designate the genotypes "B, b" on the paper by writing them on the top corners of each sheet (see instructions in Figure 2). Only students who start the first round of the game will have their genotypes pre-designated. The students who join in later through "reproduction" will use a coin toss to determine which alleles they will inherit (Figure 2). The sheets of paper for each student participating in the game should be placed along the edge of the table. Each student in the game will act as an individual bird, and their sheet of paper will represent their stomach contents. Once a student is out of the game, they will remove their sheet of paper from the table.

On the center of the table, spread out the candy so that ~60% consists of gummy worms and ~40% consists of round candy (Figure 1B). The gummy worms represent worms, and the round candy represents beetles. In the first few rounds of the game, the most abundant food source is worms. We recommend that the setup described above be completed prior to the start of class to ensure a smooth transition into the game once that point is reached during class.

At the start of the game, select ~12 student volunteers. The number of student participants can be modified as needed, depending on class size and space constraints. We are describing a method that has worked in class sizes of 200 or more students. However, with a smaller class it is possible to have all students participate by setting up two tables and dividing the class in half. Assign genotypes and phenotypes as described in Figure 2. The chopsticks and spoons represent two beak-shape phenotypes that exist in a population of birds and that are expressed by dominant-recessive alleles. The students represent the birds.

○ Playing the Game

Have the students gather around the table and ensure that each has their designated "stomach" (i.e., sheet of paper). Set a timer for 10 seconds. In that time the students will need to gather as many "insects" into their stomachs as they are able. If they are able to collect at least five, they get to "reproduce" by pairing with another successful student and tagging in two additional students as their offspring. When students "reproduce," they toss a coin to determine which of their two alleles they pass down to their

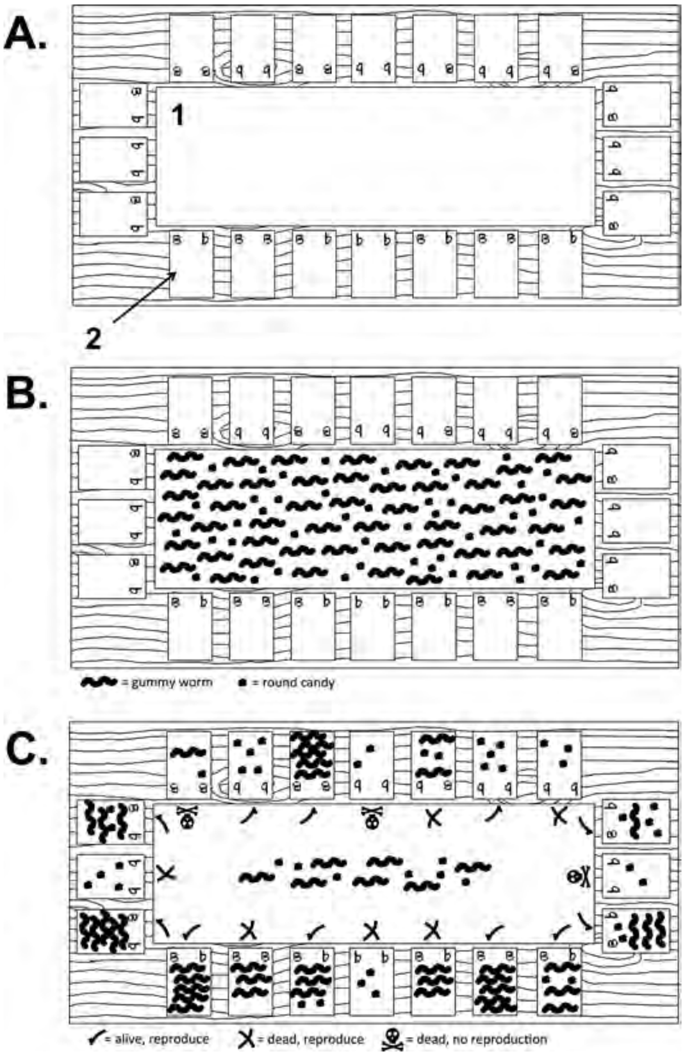

Figure 1. Diagram illustrating (**A, B**) game setup and (**C**) game play. The center space of the table represents the area in which the food source (i.e., gummy worms and round candy) for the birds will be placed, while the edge of the table is lined with participating students' sheets of paper, each representing the stomach content of an individual bird. An example of the game-play table following one round (**C**) shows that individuals who are able to collect at least five food items in their stomach contents both "reproduce" and survive to the next round (indicated by a check mark). Individuals who are able to collect at least three food items in their stomach contents "reproduce" but do not survive to the next round (indicated by an X mark). Individuals who are not able to collect at least three food items neither "reproduce" nor survive to the next round (indicated by a skull mark).

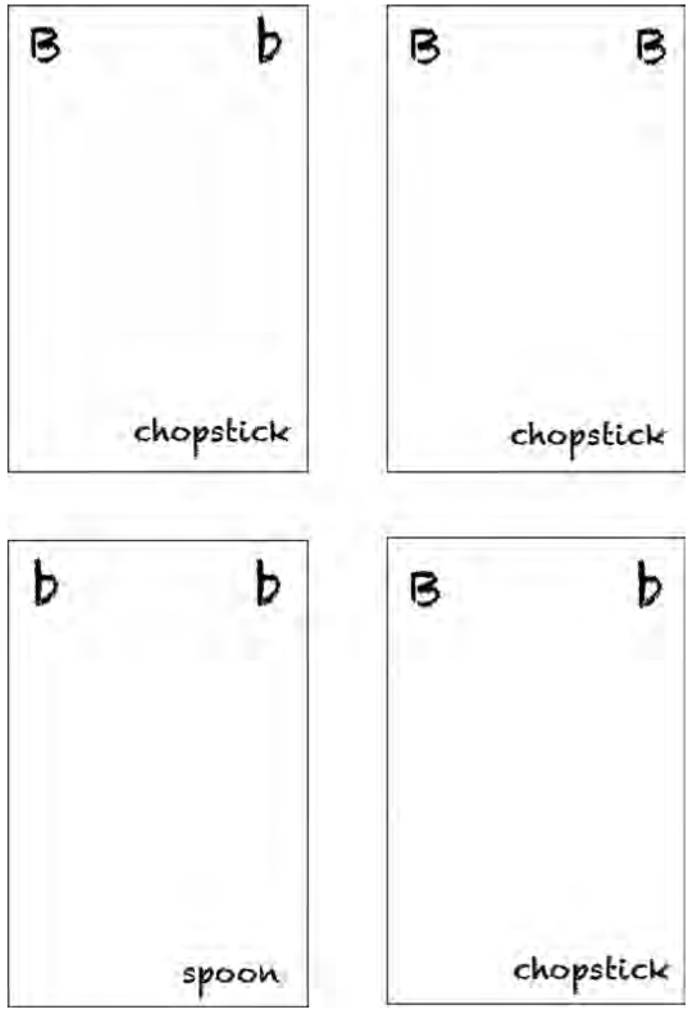

Figure 2. Example of sheets of paper assigned to students participating in the game's first round. Approximately 75% of the students in the first round should be assigned the dominant chopstick beak phenotype, and approximately 75% of those students should be assigned heterozygous genotypes (Bb), while the remaining 25% should be assigned homozygous genotypes (BB). The students who are assigned the recessive spoon phenotype should all be given the other homozygous genotype (bb).

offspring (one coin toss per offspring). If the parent flips a coin heads up, then the offspring will receive the allele on the top-left side of the parent's sheet of paper; if the coin lands tails up, then the offspring will receive the allele on the top-right side of the parent's paper. The side of the paper on which the offspring assigns their inherited alleles is randomly chosen by the offspring (i.e., they will write their two inherited alleles on the top corners of a blank sheet of paper once they determine which alleles they will get from each parent). Finally, each time a student produces an offspring, they will make a check mark on their sheet. At the conclusion of the game, the student who has produced the highest number of offspring will win the game. This method will simulate genetic inheritance of dominant/recessive alleles. Students should add a hash mark on their sheet of paper for each offspring they produce and for each additional offspring their offspring produces (i.e., descendants). If a student is able to collect at least three insects, they survive long enough to reproduce but then die and are out of the game. If they are unable to collect at least three insects, they die before they can reproduce and are out of the game/gene pool. On the board, write down the starting allele distribution of beak phenotypes (i.e., 75% chopstick, 25% spoon) and continue writing down this information following each round to record changes over time. Each round represents a generation. An example of what the table might look like after a round of game play is illustrated in Figure 1C.

After approximately four to six rounds, pause the game and explain to students that their habitat has experienced a severe drought that has caused a significant reduction in the number of worms accessible to the birds in the soil. The beetles continue to thrive due to their protective exoskeleton, which protects them from desiccation. Alter the food source accordingly so that the frequency of worms and beetles is reversed (i.e., 60% round candy, 40% worms). This alteration represents an environmental shift in response to a natural disaster. Continue playing the game for another four to six rounds.

At the end of the game, the student(s) who produced the highest number of offspring and descendants wins. Following the completion of the game, have students return to their seats (with their acquired candy bounty) and prepare to discuss the outcomes of the game.

○ Interpreting the Results

The chopsticks are more efficient for collecting the gummy worms. Therefore, during the first few rounds of the game, allele frequencies should shift in favor of the chopstick-beaked phenotype. However, following the environmental disturbance that causes the round candy to become the more abundant food source, spoon-beaked individuals suddenly gain the advantage and we see allele frequencies shift in favor of that phenotype. *One important point to emphasize is that survival itself is not key to natural selection, but rather successful reproduction is.* The Natural Selection Game takes this into account by rewarding those who are most able to reproduce, while also demonstrating that an individual who does not survive can still reproduce and remain in the gene pool.

At this point, have students break up into groups and come up with answers to the following seven questions:

Question 1. What other examples of environmental disturbances could have caused the change we experienced in food source?

Answer 1. A migration event, an environmental pollutant, a shift in climate, a natural disaster, etc.

Question 2. Explain why some birds in this population had a phenotype that was not so favorable compared to others (i.e., how do "bad" traits exist in populations?).

Answer 2. Evolution is possible because populations possess genetic variation. Genetic variation is generated continuously by random mutations and sexual reproduction. Phenotypes considered favorable at one point can be considered detrimental at any other given point.

Question 3. Would this type of natural selection work if beak shape were not a genetically linked trait (i.e., if birds could not pass their beak shape down to offspring)?

Answer 3. No. In order for natural selection to drive evolution of a trait, the trait must be passed to offspring. Only genes, and therefore genetically linked traits, are heritable.

Question 4. Some individuals who were assigned the favorable beak phenotype were not as efficient at collecting food as other individuals with the same phenotype and died off. Can you think of a real-world parallel that could explain this situation in a population?

Answer 4. You would not expect all individuals with the favorable phenotype to be equally fit. There can be other factors affecting an individual's fitness level (e.g., high parasite loads, diseases, injuries).

Question 5. Naturally, we understand why an animal would need to acquire a certain amount of food to survive (i.e., avoid starvation). But can you explain how acquiring a certain amount of food could affect an animal's ability to reproduce?

Answer 5. The need to collect a certain amount of food not only affects mate choice where only individuals who are in good condition win mating opportunities, but also reflects the physiological and energetic costs of reproduction itself.

Question 6. How do you think the outcome of the game would differ if the two phenotypes were expressed from codominant alleles rather than dominant and recessive alleles?

Answer 6. If the most frequent genotype were heterozygous, then the population would consist mostly of intermediate-beaked birds (i.e., a cross between a chopstick and spoon).

Question 7. Let's say there was another island, 100 miles away, with the same species of bird but that island did not experience drought or a shift in food availability. After 10,000 years, lowered sea levels cause a land bridge to form between the two islands, and the two populations are now back in contact with each other but they can no longer breed with each other. What do you think would have caused that?

Answer 7. Given enough time, the continuous genetic drift between the two populations will be great enough that the two populations will no longer be able to produce viable offspring if they come into contact with each other. Perhaps they can mate but their offspring are sterile (i.e., postzygotic barrier), or they now have different behaviors or morphologies that prevent them from mating (i.e., prezygotic barrier).

Once students have had time to formulate their answers, select one random group per question to discuss their answer, leading each group to the correct answer if needed. Following this discussion, the instructor should relate the results of the game to real-world examples of natural selection (e.g., the shift in beak size of medium ground finches in response to a drought event, as described above). The students, having had a chance to explore and experience natural selection on their own first, are now ready to have the instructor assign the proper vocabulary and facts of evolution to their experiences.

○ Addressing Misconceptions about Evolution

At this stage, students should be equipped to address misconceptions about evolution. To address and engage student preconceptions of evolution, we present a critical-thinking activity that addresses common misconceptions of evolutionary theory after students have had a chance to explore and experience natural selection through the simulation game. In this activity, students are broken into groups of three

Table 2. List of common sources of information that students might encounter in their research, with a description of the quality and ranking of the reliability of the contents.

Source	Description of Contents	Reliability of Information
Peer-reviewed scientific papers (e.g., *Science*, *Nature*, *Journal of Mammalogy*, *Evolution*, *Journal of Zoology*, *Proceedings of the National Academy of Sciences*)	These are considered primary sources. They represent firsthand, unfiltered, and un-interpreted information. However, it is often hard to access them without access to institutional library accounts because many are locked behind a paywall. These are OK to cite and use as references when writing a scientific paper.	Very high
Books – nonfiction, single or multiple authors, with editor(s) and references (e.g., textbooks)	These are considered secondary sources. They consist of dry interpretations of information that has been gathered from primary sources. These are OK to cite and use as references when writing a scientific paper.	High
Books – nonfiction, single author, no references (e.g., popular books)	These are perspectives and opinions of individuals. They generally do not contain data or references. They are not OK to cite when writing a scientific paper.	Highly variable
Evidence-based science reporting (e.g., *Science Daily*, *Science Magazine*, *New Scientist*)	These resources provide well-presented evidence-based science. They are useful for learning about the latest science news without having to navigate through primary sources (i.e., peer-reviewed scientific journals). They are not OK to cite when writing a scientific paper.	High
Sensationalized science reporting (e.g., IFLScience.com)	These resources tend to sensationalize science news and do not provide thorough, evidence-based reporting. They are not OK to cite when writing a scientific paper.	Low
General news (e.g., CBS, FOX, *The Atlantic*, *Time*, *Forbes*, BBC, NPR, *The Huffington Post*, *Vox*)	These contain often sensationalized and badly interpreted science. However, many also contain well-interpreted and well-presented evidence-based science. They are not OK to cite when writing a scientific paper.	Highly variable

to five, and each group is presented with at least one common misconception about evolution. If time permits, groups can address all misconceptions. Fifteen examples of common misconceptions that can be used for this activity are listed in Table 2. The students are instructed to use any resources that they deem scientifically acceptable to explore and address their assigned misconception. We suggest using Table 3 as a guide to teaching students to identify acceptable and poor sources of information. The instructor should supply the students with clear and concise prompts that include the following:

1. Using evidence, describe what evidence contradicts this misconception.
2. Describe the scientific conception behind this misconception.
3. Using evidence, provide at least one example where the scientific conception behind the misconception has been scientifically supported and observed.

Following a period of group discussion, one representative from each group is asked to present their group's findings and key discussion points to the class in an informal manner. The instructor should also write or project the accurate scientific conception to ensure that the concept is solidified for students.

This activity allows students to address specific misconceptions and also encourages them to learn what resources are scientifically acceptable and what resources are poor through trial and error. In the current age of misinformation, differentiating between reliable and unreliable sources is a critical skill (Fitzgerald, 1997). Even providing a general guideline of the reliability of sources can be problematic. For example, the dramatic increase in predatory journals and the publication of articles perceived to be peer-reviewed (and thus reliable) can be confusing for students (Batholomew, 2014). This activity allows students to seek out websites and actively discuss the issues in small

Table 3. List of 15 misconceptions about evolution and accompanying reality. This list was adapted from the Understanding Science website (https://undsci.berkeley.edu/, University of California Museum of Paleontology, Berkeley).

Misconception	Scientific Conception
Because evolution is just a theory, it is not well supported.	Evolution is a well-supported, testable, repeatable, and predictable explanation of how species have changed over time.
Evolution is a theory about the origin of life.	Evolutionary biology deals with how life changed *after* its origin, regardless of how life originated.
Humans came from monkeys.	We share a common ancestor with other primates (i.e., monkeys and apes).
Evolution and natural selection are goal-oriented.	Natural selection is the result of variation, reproductive success (or failure), and heredity. It has no goal and is not striving toward a specific end product.
Evolution is random.	Mutations are random, as are the trait that they result in. Whether or not a trait is beneficial in its environment is not random. In other words, the variation of traits in a population is random, but selection acts on whichever traits are favorable at that time and place.
You cannot see evolution happening.	We can see examples of species with short generation times changing (evolving) over time (e.g., pesticide resistance in insects, antibiotic resistance in bacteria, shift in body size in fish).
Individual organisms can evolve within their life span.	Populations are the smallest unit of life that can evolve. Individuals cannot evolve. However, an individual can experience a mutation in its gametes (i.e., in its heritable genetic makeup) that contributes to the process.
Natural selection is the only mechanism by which organisms evolve.	Evolution can occur through natural selection, artificial selection, mutation, migration, and genetic drift.
Species will always evolve what they need to survive.	Species that cannot adapt fast enough to changes in the environment will die off. Species do not always get what they need.
Natural selection produces organisms perfectly suited for their environment.	Adaptations do not have to be perfect – just good enough to allow an organism to pass its genes to offspring.
"Survival of the fittest" means survival of the strongest.	"Survival of the fittest" refers to biological fitness – in other words, surviving long enough to reproduce.
Humans are no longer evolving.	Humans still face challenges to survival and reproduction and experience change over time (e.g., region-specific lactose intolerance and malaria resistance).
Natural selection involves organisms trying to adapt.	Natural selection leads to adaptation over time but does not involve effort. Either an individual has genes that are good enough to survive and reproduce or it does not; it cannot obtain the right genes by "trying."
Evolution is a theory in crisis and is collapsing as scientists lose confidence in it.	Evolutionary theory is not in crisis. Scientists do not debate whether evolution took place, but they do debate many details of how evolution occurred/occurs.
Evolution always leads to more complex organisms.	Evolution leads to change in species over time, but it may or may not increase the complexity of anatomy or physiology.

groups and with the instructor. This approach opens a dialogue to address misinformation issues and pushes students to defend their chosen site as "reliable." Besides allowing students to discuss the reliability of the sources they choose, this activity gives them power to engage in learning about their own potential misunderstandings while providing them time to share their findings with others.

○ Concluding Remarks

Teaching complex biological processes can be a challenge, especially in large lecture settings. Certain topics, such as evolution, can add additional challenge due to the political and religious underpinnings surrounding the theory. However, it is imperative that students are able to address common misconceptions and understand the complex mechanisms so that they can become scientifically literate. We present these paired activities in hopes that other instructors can utilize them in their own classrooms to help combat scientific illiteracy.

○ Acknowledgments

We are grateful to the spring 2017 Biology 1010 class at Utah State University for allowing us to test and refine these lessons. We are also grateful to Emily Kane at Georgia Southern University for encouraging us to publish these teaching activities, and to Mathilde Cordellier at Universität Hamburg who provided excellent suggestions for improving our simulation game. Finally, we thank the anonymous reviewers, whose recommendations greatly improved our paper.

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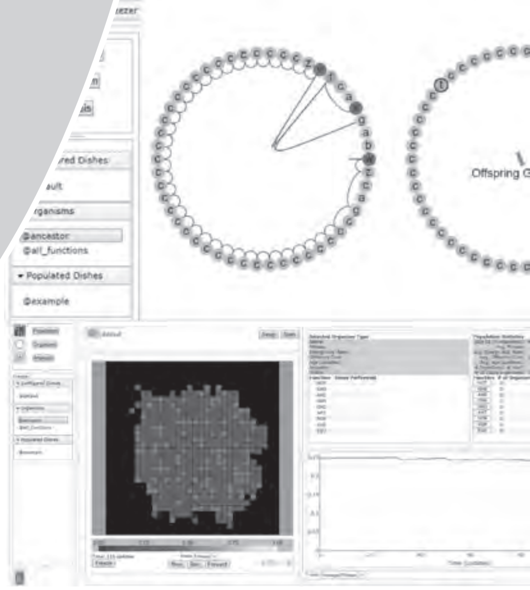
INQUIRY & INVESTIGATION

Evaluating the Use of Avida-ED Digital Organisms to Teach Evolution & Natural Selection

RECOMMENDED FOR *AP Biology*



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Abstract

The concepts of evolution and natural selection remain as some of the most challenging topics to teach. The difficulty in teaching these topics arises from the fact that evolution is difficult to observe, and computer simulations do not always result in a clear understanding of evolutionary principles. Recently, the Avida-ED software has been developed to simulate evolution in a laboratory setting. Unlike other simulations, Avida-ED allows students to manipulate the environment, change the genetics of the virtual organisms, and track offspring in real time. We have demonstrated, by using pretest and posttest questionnaires, that students gained a deeper understanding of evolutionary concepts by using this software. In particular, students showed the greatest increase in their ability to explain evolutionary concepts in answers to open-ended questions. Our results show that Avida-ED could be a useful tool in helping students understand and combat preconceived notions about evolution.

Key Words: *Avida-ED; evolution; natural selection; digital evolution.*

○ Introduction

The concept of evolution is one of the core and unifying principles of biology. In the words of the great evolutionary biologist Theodosius Dobzhansky, "nothing in biology makes sense except in the light of evolution" (Dobzhansky, 1973). Additionally, the principles underlying evolution have been validated by scientists and science education organizations, both in the United States and around the world (Plutzer & Berkman, 2008; Wiles, 2010; Bramschreiber, 2013). Yet evolution is considered one of the most controversial and difficult topics for instructors of biology to teach in the United States, where the theory still faces a wide range of scrutiny and lack of acceptance among much of the general public. In fact, polling data collected since 1984 indicate that 40–47% of U.S. adults consistently state that they believe humans were created in their present form within the past 10,000 years (Pobiner, 2016). This is radically different from the views held by the majority of adults in European countries and Japan, where approximately 60–80% of adults accept the idea of evolution (Miller et al., 2006). Hence, there is a great need for in-depth and engaging evolutionary instructional tools for the enhancement of evolutionary understanding in U.S. populations.

"Unlike other simulations, Avida-ED allows students to manipulate the environment, change the genetics of the virtual organisms, and track offspring in real time."

Furthermore, teaching the ideas of complex evolutionary theory can be a challenge for instructors. For instance, direct observations and the quantification of evolution are difficult in any setting, and can be especially difficult in the college classroom and/or laboratory setting. Additionally, given the integrative nature of evolution in the field of biology (with overlapping subfields including molecular biology, cellular biology, and microbiology, among others), the facilitation of a deeper understanding of evolutionary ideas is even more difficult (Nehm et al., 2009). Many resources, including in-depth case studies (White et al., 2013) and interactive laboratory simulations (Abraham et al., 2009), are available for instructors to use in the dissemination of evolutionary concepts to students. However, these resources are not adequate for helping undergraduate students master evolutionary principles, because of various factors – such as cost-prohibitive equipment/software for analyzing evolution and the inability to directly observe and experimentally manipulate various aspects of evolutionary theory in a research setting.

More recently, an instructional method that uses a digital organismal model has been utilized to help overcome the difficulties of teaching evolution. Specifically, the research platform known as Avida-ED, which was first developed at Cal-Tech in

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the late 1990s and has been further developed as an educational tool at Michigan State University (Ofria & Wilke, 2004; Pennock, 2007), allows students to directly observe self-replicating virtual organisms (Avida) that behave in ways similar to bacteria. Additionally, this simulation program allows students to witness evolutionary principles in a real-time setting, which is of tremendous benefit to students. A major advantage of the Avida-ED program that distinguishes it from other evolutionary simulations is that students can study and analyze evolution in an experimental setting. Users have the ability to manipulate resources in the environment, change mutation rates, and track generations of these organisms to observe how these components can alter natural selection. The use of Avida-ED in both experimental and educational settings has become widespread in recent years and has been associated with enhanced student success in learning evolutionary principles (Lenski et al., 2003; Misevic et al., 2006; Clune et al., 2011; Grabowski et al., 2013; Zaman et al., 2014; Smith et al., 2016; Lark et al., 2018).

Given the reported success of Avida-ED in educational settings, we designed a study to investigate whether the implementation of Avida-ED in a first-semester freshman introductory biology course could result in significant increases in the understanding of evolutionary ideas and principles at a liberal arts college in a rural setting. Previous studies have investigated the link between rurality and acceptance of evolutionary ideas, with data exhibiting varying degrees of significance in regard to whether individuals in rural settings accept evolutionary theory (Mazur, 2004; Baker, 2013). Specifically, we used pretest and posttest questionnaires to examine whether Avida-ED was effective in increasing the knowledge and retention of basic evolutionary principles, such as the roles of random mutations, competition, and natural selection. Overall, by comparing students' pretest and posttest responses, we found that the use of Avida-ED increased students' understanding of ideas that are central to the theory of evolution. Our results demonstrate how Avida-ED can be used as a valuable tool in evolution education in small colleges and universities.

○ Methods

Student Population

Thiel College is a liberal arts college in Greenville, Pennsylvania, that primarily serves students from Pennsylvania, Ohio, and New York. The student population consists largely of individuals from nearby rural counties in these states, many from low-income backgrounds. The Avida-ED lab was used as a part of the laboratory portion of Foundations of Biology (BIO 145), a one-semester introductory course that is required for all majors in the biology department and is a prerequisite for all other biology courses. Data were gathered from 125 students between fall 2016 and fall 2018 (a total of five semesters and pooled from 10 different sections of the course taught by six different instructors). The students included freshman biology majors as well as nonmajors taking the course to fulfill their science core curriculum requirement. The Avida-ED labs were performed in the laboratory sections prior to any instruction on evolution in the lecture portion of the course.

Avida-ED Software

The Avida-ED software used in this study is freely available from the developing team at Michigan State University and can be found at https://avida-ed.msu.edu/avida-ed-application/. Students used either the web version or the downloaded software on their individual computers. There were no differences in experimental setup between the two versions.

Avida-ED Experiments & Lab Design

Students followed the Avida-ED curriculum that was generated by the design team at Michigan State University. Specifically, Thiel College faculty members implemented the model lessons found in the Avida-ED lab book and curriculum (https://avida-ed.msu.edu/curriculum). The laboratory instruction was divided into two sections spread over two weeks. Week 1 started with students taking a pretest questionnaire that measured their understanding of evolutionary principles prior to any Avida-ED instruction (or any teaching of evolutionary concepts in lecture). Week 1 also focused on introducing the software to the students so that they could become familiar with the tools and features of the program. Once they had become familiar with the software, and all the software-related questions had been addressed, students ran their first experiment: "Exercise 1: Understanding the Introduction of Genetic Variations by Random Mutation." This concluded week 1 of Avida-ED instruction. Week 2 resumed with the second and third experiments: "Exercise 2: Exploring Fitness, Functions, and Selection" and "Exercise 3: Exploring Mutations and Selection: Pre-adaptive or Post-adaptive?" Week 2 activities ended with a posttest questionnaire (identical to the pretest questionnaire). This progression is shown in Figure 1.

Questionnaire

The (identical) pretest and posttest questionnaires were conducted in the laboratory at the beginning of week 1 and at the end of week 2. The laboratory sessions that focus on evolution occur before that material is discussed in the lecture component of the course. The questionnaire is based on questions from the Conceptual Inventory of Natural Selection (Anderson et al., 2002) and from questions provided by the Active LENS Train-the-Trainers Workshop at Michigan State University (which the

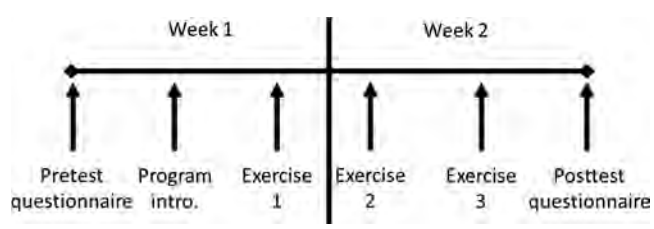


Figure 1. Avida-ED instruction design and assessment questionnaire timeline. In week 1, students in a freshman-level introductory biology course were given a prettest questionnaire to evaluate their understanding of evolutionary principles, later were introduced to the Avida-ED software, and subsequently performed Exercise 1. In week 2, students performed Exercises 2 and 3 and then completed the posttest questionnaire.

authors attended in 2015). The students had the option of choosing whether to participate in the pretest and posttest questionnaires and had the option of opting out (the study was approved by the Institutional Review Board Committee of Thiel College); however, all students in the course were required to participate in the Avida-ED simulation as part of their lab grade for the two lab periods. Students were not compensated for their time, neither monetarily nor in grade form. Several students declined to participate in the questionnaire. Over a period of five semesters, a total of 10 course sections were involved in the study and a total of 125 pretest and posttest questionnaires were collected. All the questions that were administered are available in the Supplemental Material with the online version of this article.

Questionnaire Analysis, Data Entry & Statistics

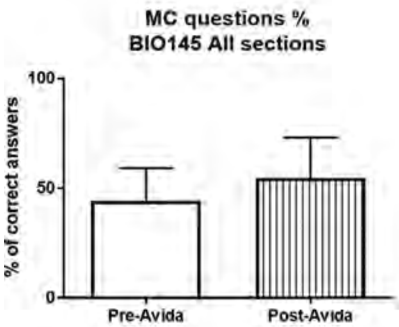
Questionnaires were graded by either professors or teaching assistants, strictly following a key of correct responses for multiple-choice (MC) questions and acceptable responses for open-ended (OE) questions. Data were entered into Excel and were graphed and analyzed in Prism 7.04 (GraphPad, San Diego, California).

○ Results

Analysis of students' responses to MC and OE questions before Avida-ED instruction (pre-Avida) and after Avida-ED instruction (post-Avida) (N = 125 students between 2016 and 2018; see above) demonstrated positive effects. Mean percentages of correct MC responses were significantly different between the pre-Avida and post-Avida response groups; specifically, the mean percentage of correct MC responses increased from 44.31 for the pre-Avida instruction group (95% confidence interval [CI]: 41.68–46.95) to 54.61 for the post-Avida instruction group (95% CI: 51.33–57.88) ($P < 0.001$) (Figure 2). There was an even more significant difference in the OE responses between the pre-Avida and post-Avida response groups; specifically, the mean percentage of acceptable OE responses increased from 43.6 for the pre-Avida instruction group (95% CI: 39.16–48.04) to 69.68 for the post-Avida instruction group (95% CI: 64.93–74.43) ($P < 0.001$) (Figure 3).

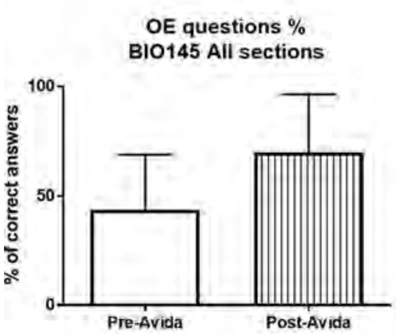
Mean fold changes from pre-Avida to post-Avida instruction for both the MC and OE questions were also analyzed. There was a mean fold change of 1.331 (95% CI: 1.224–1.438) in the MC responses (Figure 4) and a mean fold change of 2.096 (95% CI: 1.799–2.393) in the OE responses (Figure 5).

Finally, to determine how much Avida-ED helped (or potentially hurt) students' understanding of natural selection, we compared the number of answers from the pretest to posttest questionnaire that went from wrong to right (W to R) with the number that went from right to wrong (R to W) (Figure 6). We found that there was a significant increase in the "W to R" answers compared to the "R to W" answers when looking at both MC and OE questions.



	Pre-Avida	Post-Avida
Minimum	13.04	13.04
25% Percentile	34.78	39.13
Median	43.48	52.17
75% Percentile	52.17	69.57
Maximum	91.3	95.65
Mean	44.31	54.61
Std. Deviation	14.88	18.5
Std. Error of Mean	1.33	1.655
Lower 95% CL of mean	41.68	51.33
Upper 95% CL of mean	46.95	57.88
Paired t test		
P value		<0.0001
P value summary		****
Significantly different (P < 0.05)?		Yes
One- or two-tailed P value?		Two-tailed

Figure 2. Students' (N = 125) average performance on a series of multiple-choice (MC) questions that tested their understanding of evolutionary principles. The mean percentage of correct responses before Avida-ED instruction (pre-Avida) was 44.31%. The mean percentage of correct responses after Avida-ED instruction (post-Avida) was 54.61%. The data are statistically significant (****$P < 0.0001$). The tables show minimum and maximum values, 25% and 75% percentiles, median, mean, standard deviation, standard error, lower and upper 95% confidence limits, and the results of statistical analysis.



	Pre-Avida	Post-Avida
Minimum	0	10
25% Percentile	25	50
Median	40	70
75% Percentile	60	90
Maximum	100	100
Mean	43.6	69.68
Std. Deviation	25.09	26.82
Std. Error of Mean	2.244	2.399
Lower 95% CL of mean	39.16	64.93
Upper 95% CL of mean	48.04	74.43
Paired t test		
P value		<0.0001
P value summary		****
Significantly different (P < 0.05)?		Yes
One- or two-tailed P value?		Two-tailed

Figure 3. Students' (N = 125) average performance on a series of open-ended (OE) questions that tested their ability to describe evolutionary principles. The mean percentage of acceptable responses before Avida-ED instruction (pre-Avida) was 43.60%. The mean percentage of acceptable responses after Avida-ED instruction (post-Avida) was 69.68%. The data are statistically significant (****$P < 0.0001$). The tables show minimum and maximum values, 25% and 75% percentiles, median, mean, standard deviation, standard error, lower and upper 95% confidence limits, and the results of statistical analysis.

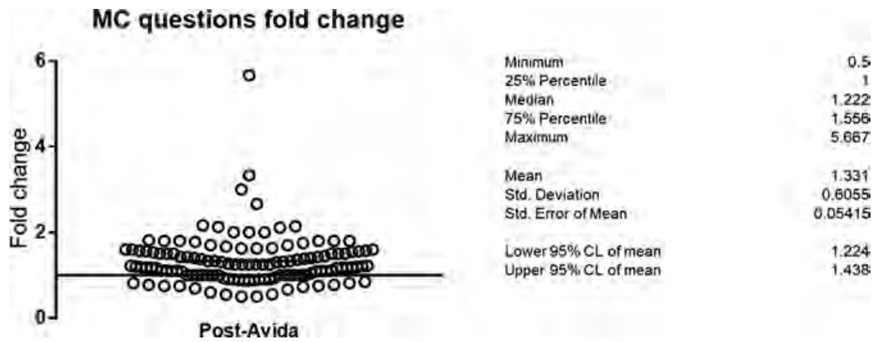


Figure 4. Students' (N = 125) fold change in performance between pretest and posttest questionnaires on a series of multiple-choice (MC) questions that tested their understanding of evolutionary principles. The graph shows the fold change in percentage of correct responses calculated following Avida-ED instruction (post-Avida). The mean fold change is 1.331. The table shows minimum and maximum values, 25% and 75% percentiles, median, mean, standard deviation, standard error, and lower and upper 95% confidence limits.

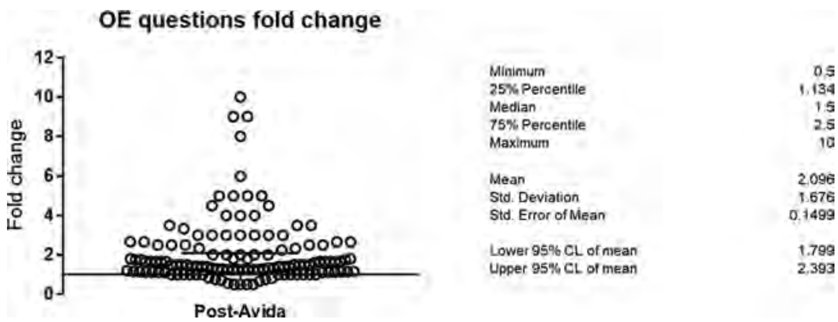


Figure 5. Students' (N = 125) fold change in performance between pretest and posttest questionnaires on a series of open-ended (OE) questions that tested their understanding of evolutionary principles. The graph shows the fold change in percentage of acceptable responses calculated following Avida-ED instruction (post-Avida). The mean fold change is 2.096. The table shows minimum and maximum values, 25% and 75% percentiles, median, mean, standard deviation, standard error, and lower and upper 95% confidence limits.

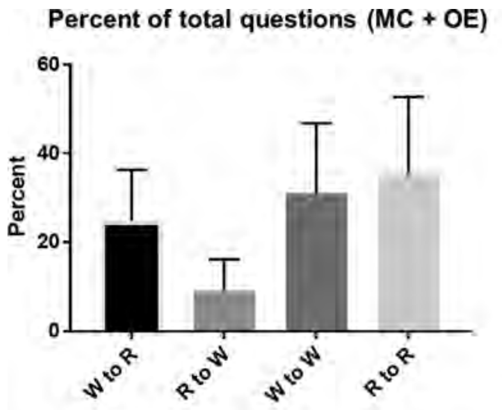
○ Discussion

Evolution is one of the most difficult and controversial topics to teach in the biological sciences. Based on previous research concerning evolutionary instruction, it is thought that students have difficulty with both the understanding and the acceptance of evolutionary theory; and a greater degree of acceptance sometimes does not result in increased understanding, and vice versa (Sinatra et al., 2003). We examined whether the implementation of the innovative evolution simulation program Avida-ED, which allows students to manipulate organisms in an experimental setting, would increase and enhance introductory biology students' understanding and retention of evolutionary concepts. Our results demonstrate significant increases in the ability of these students to recall and retain important evolutionary concepts.

These results are consistent with previously reported data on the efficacy of the Avida-ED activities in both a high school and a university/college setting (Lenski et al., 2003; Misevic et al., 2006; Clune et al., 2011; Grabowski et al., 2013; Zaman et al., 2014; Smith et al., 2016; Lark et al., 2018). While there were significant increases in the percentage of correct responses from pretest to posttest for both MC and OE questions, the most significant effect we observed was the increase in correct OE responses (26.08% improvement, compared to 10.30% improvement on MC questions). The ten OE questions asked students to explain concepts rather than simply identify correct answers. The greater increase in acceptable OE answers may indicate that Avida-ED helps students gain a better ability to describe evolutionary processes. While Avida-ED also helped with the declarative knowledge tested by the MC questions, an integrated active-learning tool like Avida-ED may not be as effective in increasing comprehension at this lower level of thinking. Similar results have been found in other areas of biology education research, where active-learning tools such as flipped classrooms have increased deep learning but not surface learning (Lax et al., 2016). Future studies will have to investigate whether or not active-learning laboratory activities like Avida-ED help with long-term retention and understanding of the material over time.

The Conceptual Inventory of Natural Selection from which our pretest and posttest questionnaire is derived (Anderson et al., 2002) was written as a way to test many of the principles central to understanding the theory of evolution – specifically, how natural selection works. The concepts include biotic potential, carrying capacity, limited resources, limited survival, genetic variation, origin of variation, heritability of variation, differential survival, change in population, and origin of species. The questions are also written in such a way that the students do not have to be familiar with the particular jargon associated with the topic to successfully understand the content of the question. This means that students with no background could potentially score well on the pretest and posttest. However, one aspect of our questionnaires that was not investigated was how well students improved in their understanding of these different aspects of evolution by natural selection. Future studies will look into how, if at all, Avida-ED helps students improve in these different areas.

While our results demonstrate that students can benefit significantly from the use of Avida-ED, we acknowledge that our study has some limitations. One limitation is evident in the structure and makeup of our assessment tests. Both the MC and OE portions of the pretest and posttest questionnaire focused on basic, foundational principles of evolution such as which organisms are the most "fit," how natural selection involves differences in traits, and how genetics/mutations may affect evolution. In order to more accurately measure the performance and understanding of our students,



2Way ANOVA

Tukey's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Significant?	Summary	Adjusted P Value
W to R vs. R to W	15.66	10.59 to 20.72	Yes	****	<0.0001
W to R vs. W to W	-6.181	-11.25 to -1.116	Yes	**	0.0095
W to R vs. R to R	-10.7	-15.77 to -5.638	Yes	****	<0.0001
R to W vs. W to W	-21.84	-26.9 to -16.77	Yes	****	<0.0001
R to W vs. R to R	-26.36	-31.42 to -21.29	Yes	****	<0.0001
W to W vs. R to R	-4.521	-9.586 to 0.5431	No	ns	0.0990

Figure 6. Students' ($N = 125$) performance on a series of multiple-choice (MC) and open-ended (OE) questions that tested their understanding of evolutionary principles. The graph shows the percentage of answers that switched from wrong to right (W to R) or from right to wrong (R to W) between the pretest and posttest questionnaires. The graph also shows the percentage of questions that were answered either incorrectly (W to W) or correctly (R to R) in *both* the pretest and posttest questionnaires. The table shows the results of a two-way analysis of variance (ANOVA) with a Tukey's multiple comparison. The difference between "W to R" and "R to W" is statistically significant (****$P < 0.0001$).

multiple assessment techniques that measure both "concept knowledge" and "process knowledge" could be used, as described by Speth et al. (2009). This approach could also increase students' abilities to apply and transfer their evolutionary knowledge to different contexts and evolutionary scenarios. Additionally, the fact that they were asked to complete an identical assessment questionnaire both before and after the experiment may have sensitized the students to the relevant concepts and issues concerning evolution, thus resulting in increased student understanding (the "practice" effect). However, given that this was the first time that these students had been exposed to college-level evolutionary instruction at Thiel College, we are convinced that this two-week Avida-ED module produced significant increases in student understanding. In order to further elucidate the effects of Avida-ED instruction and validate these significant results, future studies should include a control/comparison group of students who do not receive the Avida-ED instruction.

Furthermore, with the baseline results presented in this experiment, an opportunity arises to incorporate the performance of more advanced Avida-ED experimental modules in the curriculum. Specifically, this software could be used in a semester-long evolution course to allow students to comprehend more advanced, complex evolution concepts. In this way, a future study could investigate the semester-long impact of Avida-ED in bolstering evolutionary understanding and comprehension.

One other major limitation to this study is the fact that the pretest and posttest questionnaires do not address the question of acceptance of evolutionary theory. The rejection of evolutionary theory by a large proportion of U.S. adults is thought to involve factors that include a literal interpretation of the Bible, political views, and education status (Miller et al., 2006; Hokayem & BouJaoude, 2008; Plutzer & Berkman, 2008; Nelson, 2012; Newport, 2012; Pobiner, 2016). The immediate rejection of evolution by some students and their misconceptions about evolution present a problem to instructors who wish to accurately teach the concepts of evolution to undergraduate students. Some studies have observed a positive relationship between evolutionary understanding and acceptance (Rice et al., 2011; Akyol et al., 2012), while others have not observed the same positive association (Nehm & Schonfeld, 2007). Regardless, the goal of teaching evolution to undergraduate students is not simply to ensure that they understand this concept; we also hope they will discover for themselves that the evidence-based theory of evolution is the most plausible explanation that scientists have for describing the unity and diversity of life on Earth. Allowing students to see that there is scientific consensus and evidence behind seemingly controversial topics could lead to greater acceptance of other controversial ideas such as climate change and vaccines (Kudrna et al., 2015; Walker et al., 2017). In the future, specific assessment strategies and questions can be adapted from other studies that have investigated evolutionary acceptance (Lark et al., 2018), which will allow us to determine if there is a positive association between students understanding evolutionary theory and accepting it, following the use of Avida-ED.

Finally, it is easy for instructors to incorporate Avida-ED into any biology course, large or small. It has a simple, easy-to-use interface, a relatively straightforward learning curve, and, most importantly, it costs nothing. Additionally, after learning how to use Avida-ED in an introductory lab setting, students may then be able to use the program for more complicated lab assignments or for independent study projects in specific lab courses. Given that evolution is considered a significantly difficult concept to teach, the documented ability of Avida-ED to promote and enhance student understanding is a significant benefit for instructors and students alike. Based on our significant results obtained from the analysis of various introductory biology cohorts, it is logical to assume that a similar benefit can be obtained from the implementation of this simulation program in other upper-level evolution courses, including courses on human evolution and population genetics, or in an undergraduate independent research course for senior students. Furthermore, the accessibility and proven benefits of this software would make it ideal for high school instruction of evolution as well.

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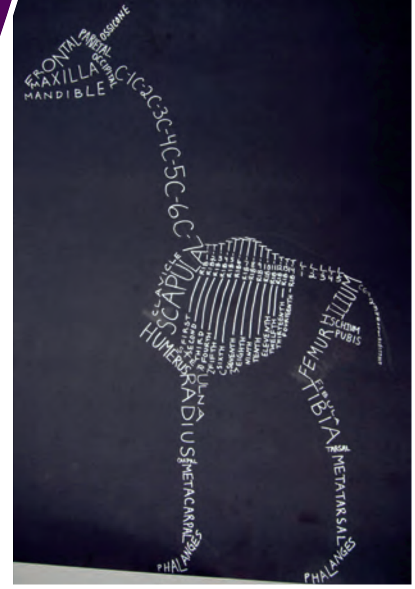
TIPS, TRICKS & TECHNIQUES

Using Skeleton Typograms to Explore Comparative Anatomy



NABT BioClub RECOMMENDATION

CATHERINE HIBBITT

Abstract

A highlight activity of the author's comparative anatomy class, this skeletal typogram activity challenges students to take their understanding of the skeletal system's components beyond mere memorization of bone names and locations. Each student creates a poster of a vertebrate skeleton, using the letters of the bone names to depict the actual bone shape and location. Animals are chosen by the teacher to represent a wide variety of evolutionary adaptations (swimming, flying, grazing, hunting, etc.). Students are then asked to compare the different typograms through analysis of contrasting skeletal evolutionary adaptations. The infographic nature of the project helps students understand the power of visual information, allowing for creative cross-disciplinary work. Through developing and comparing typograms, students deepen their understanding of how skeletal form fits function and the role of adaptation in vertebrate evolution.

Key Words: *anatomy; comparative anatomy; skeletal systems; evolution; infographic; cross-disciplinary work; typogram.*

Several years ago, while searching the Internet for a skeleton image for a human bones quiz, I found a human skeleton typogram created by Aaron Kuehn (Figure 1). This is how Kuehn described the work: "Here it is . . . a 2 dimensional static representation of long-stride locomotion! The component bones, ordinarily constructed with rigid mineralized tissues, have been entirely *typo-grammatically* replaced with 676 free and fused glyphs, together forming a complete skeletal diagram in LATIN. A radically literal graphic abstraction of anatomy" (https://alltop.com/viral/bone-up-on-anatomy-with-the-skeleton-typogram). This imaginative depiction of the human skeleton became the basis for a yearly project, one of the activities my comparative anatomy students have noted as a highlight of the course.

> *"Through developing and comparing typograms, students deepen their understanding of how skeletal form fits function and the role of adaptation in vertebrate evolution."*

My one-semester Comparative Anatomy and Physiology elective is designed to give sophomore through senior high school students a basic understanding of mammalian anatomy and physiology. Students first learn basic human anatomy and physiology. In some activities, this becomes the groundwork for comparing tetrapod evolution for widely differing activities such as flight, hunting, burrowing, diving, and more. The course emphasizes project-based learning activities such as the skeleton typogram, allowing students to take imaginative ownership of their learning.

The skeleton typogram activity follows the "Bones Race," in which students learn 29 major bones of the human body through a challenge to indicate them on the classroom skeleton in less than a minute (Figure 2). Despite initial cries of horror, after practice most students complete the task well within the allotted time. Students are given time in class to practice, both alone and in pairs. They also receive pointers to make the task as achievable as possible, such as naming bones in the same order each time, naming them from head to foot, and recognizing naming patterns (for example, phalanges are phalanges on any limb). A few minutes of both class time and homework time are allotted to practice for a week. Students then do the "Race" individually in front of their supportive classmates. The order in which they go is not significant, as any student completing the task receives a perfect score, and watching their classmates successfully complete the task generally encourages more hesitant students. Students truly nervous of performing in front of the class are allowed to come individually outside of class time to complete the task with just the teacher present. This introductory activity establishes student familiarity with the names, shapes, and placement of the major bones or bone groups of the human skeleton. However, there is not much intellectual excitement in being able to simply name

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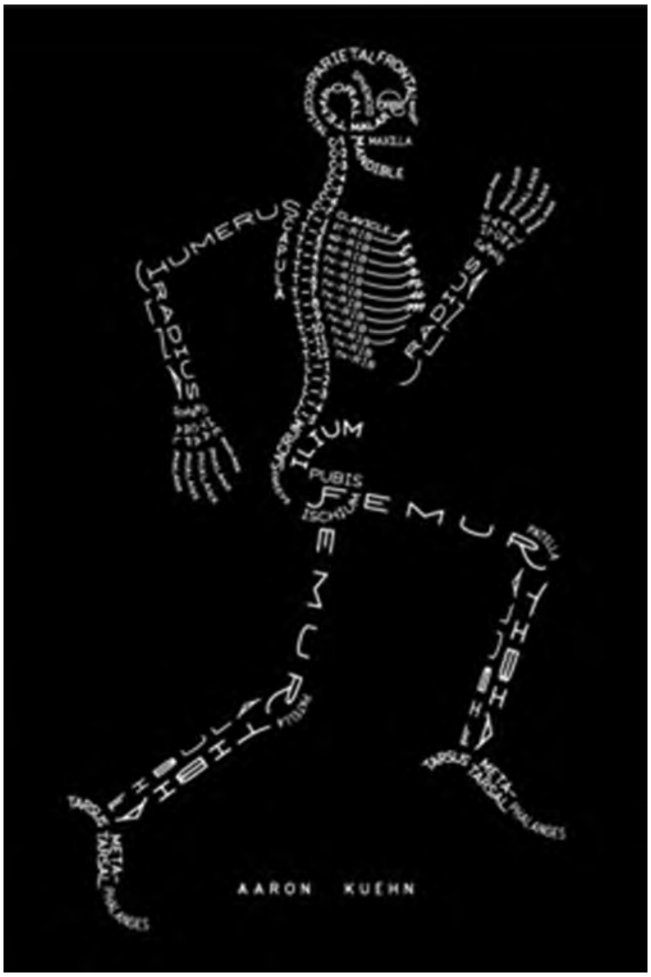

Figure 1. Skeleton typogram by Aaron Kuehn.

Bones Race Checklist Name: ____________

Skull (Cranium) ______
Maxilla ______
Mandible ______
Zygomatic arch ______
Cervical vertebrae ______
Thoracic vertebrae ______
Lumbar vertebrae ______
Clavicle ______
Scapula ______
Sternum ______
Ribs ______
Humerus ______
Ulna ______
Radius ______
Carpals ______
Metacarpals ______
Phalanges (hand) ______
Ilium ______
Ischium ______
Pubis ______
Sacrum ______
Coccyx ______
Femur ______
Patella ______
Tibia ______
Fibula ______
Tarsals ______
Metatarsals ______
Phalanges(foot) ______

Time: ______

Figure 2. Bones Race checklist.

bones (although cheering each other on during the Bones Race is fun). True understanding of the bony structure comes with appreciation of how comparative shape, size, and placement of the same bones in different species reflect evolutionary responses to different challenges for survival. Life on Earth shows amazing adaptations developed over evolutionary time, and skeletal adaptations of tetrapods provide many examples.

In the typogram activity, each student is given the name of a different animal, which I select as interesting representatives of vertebrate skeletal adaptations (Figure 3). Students then create a typogram of their assigned mammal on poster board. They are asked to include at least all the bones from the Bones Race; they often find that there are very interesting adaptations of other bones to include. Accompanying each poster, students write a one-page description of their

1. Gibbon
2. Turtle
3. Horse
4. Eagle
5. Tuna
6. Crocodile
7. Giraffe
8. Elephant
9. Fruit bat
10. Cheetah
11. Right whale
12. Narwhal
13. Komodo dragon
14. Albatross
15. Dolphin
16. Anteater
17. Kangaroo
18. Gorilla
19. Kangaroo
20. Burmese python
21. Mole
22. Pterodactyl
23. Anteater
24. Polar bear
25. Hummingbird

Figure 3. List of animals assigned for skeleton typogram projects.

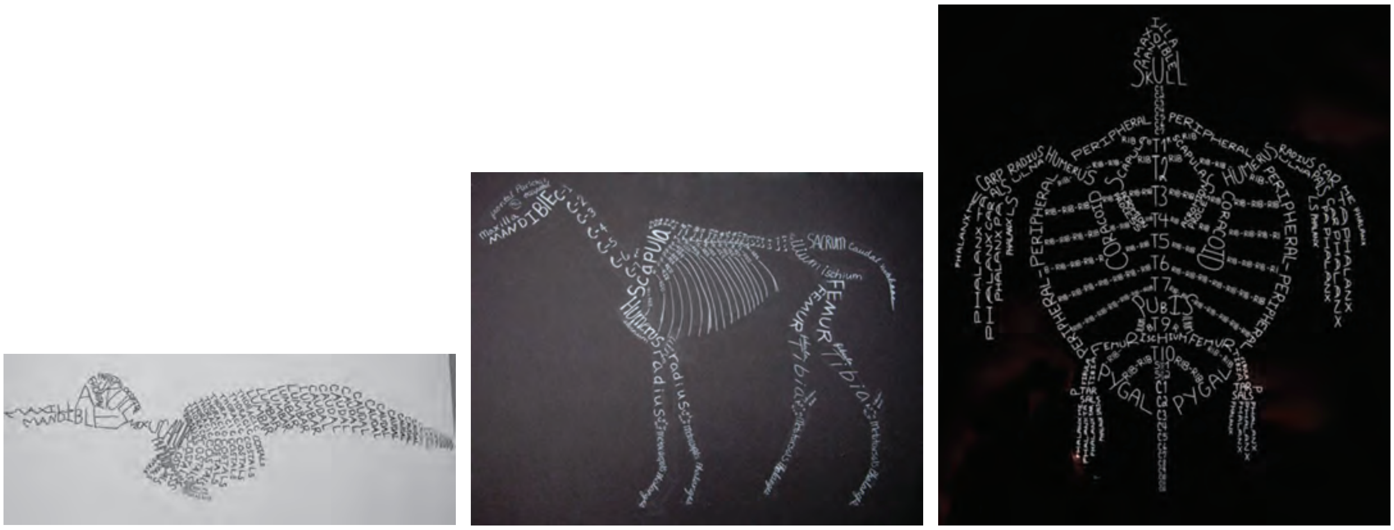

Figure 4. Student typograms. From left to right: dolphin, horse, sea turtle.

Element	Accuracy (all bones included)	Clarity/ careful completion	Written explanation	Two things you (the reviewer) find fascinatingly different from the skeleton you drew, with explanation of these adaptations
	5 – yes 3 – a few missing (unless the animal doesn't have it) 1 – many missing	5 – excellent – very easy to read/ understand 4 – very good 3 – good 2 – somewhat difficult to read/understand 1 – very difficult to read/understand	5 – excellent – interesting and relevant information about animal's evolutionary skeletal adaptations 4 – very good 3 – good 2 – some useful/ interesting information about animal's evolutionary skeletal adaptations 1 – very little useful information	
Score and notes				

Figure 5. Skeleton typogram grading rubric.

animal, focusing on the bony adaptations that allow it to do what it does – run, slither, climb, swim, and so on. A list of assigned animals is provided (Figure 3), but there are potentially many more choices highlighting tetrapod evolution.

The projects are inevitably varied, interesting, and imaginative (Figure 4). We hold a celebratory anatomy zoo in which students review and learn from each other's work. A basic checklist/rubric is used for each student to both evaluate and learn from the details of each poster (Figure 5). The same rubric is used by the teacher for grading the project, excluding the final "What did you find different?" column. Note that a score for artistry is not included; this is important in emphasizing the learning that all students can do through the project rather than specifically rewarding the subset with more artistic skill or experience. The zoo is then hung in the hallway to share and be enjoyed by the student body as a whole. Following completion of this activity, it is evident that students have developed both a solid understanding of basic skeletal structure and an appreciation for how variations reflect evolutionary adaptation to survival in differing environmental challenges.

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TIPS, TRICKS & TECHNIQUES

EvMedEd: A Teaching Resource for Integrating Medical Examples into Evolution Education

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Abstract

Teaching evolution using medical examples can be a particularly effective strategy for motivating students to learn evolutionary principles, especially students interested in pursuing medical and allied health careers. Research in the area of evolutionary medicine has expanded the number of ways in which evolution informs health and disease, providing many new and less widely known contexts that can be adopted for classroom use. However, many instructors do not have time to locate or create classroom materials about evolutionary medicine. To address this need, we have created EvMedEd, a resource repository to help instructors who want to integrate more medical examples into their evolution instruction or instructors who are teaching a course on evolutionary medicine. Some resources are designed to be more appropriate for a high school or introductory biology audience, whereas others are more advanced. We encourage instructors to access this curated website and to share their own teaching materials with this community.

Key Words: *evolution; health; medicine; evolutionary medicine; online resource; student-centered.*

Medically relevant applications of evolutionary principles illustrate how evolutionary biology is important to our day-to-day lives (Varki, 2012). However, increased awareness of the growing number of ways in which evolution informs an understanding of health and disease would be useful for evolution instructors. Here, we introduce EvMedEd.org, an online resource to help instructors integrate medically relevant examples of evolution into their biology courses or develop their own course devoted to evolutionary medicine – a multidisciplinary field focused on these applications.

○ Why Teach Evolution through Medical/Health Examples?

Many students whose interest in the life sciences stems from a desire to work in medicine or allied health careers (Cooper et al., 2019) may not realize that evolution is relevant to their career interests. Evolution is not only a core concept in biology (AAAS, 2011; Brownell et al., 2014), but is now a core competency for pre-medical students (AAMC-HHMI, 2009). While medical professionals are traditionally taught how disease happens, a foundation in evolutionary biology equips them to also understand why their patients are vulnerable to disease in the first place (Nesse et al., 2010).

Using medically relevant examples to teach evolutionary principles can help build and maintain student interest in learning evolution (Antolin et al., 2012), particularly for students interested in health careers. Motivational theories of learning suggest that content relevance is a key ingredient for designing stimulating learning experiences (Keller, 2009). Perceiving that a task, such as learning evolution, is important for one's own goals has been shown to be important for student persistence in obtaining that goal (Wigfield & Eccles, 1992). Thus, when designing evolution instruction to engage pre-health students, those students may benefit from the use of medical examples that make explicit how evolution is relevant to both their personal lives and their career interests (Keller, 2009). With the potential for increased student motivation and growing recognition that evolution is an important basic science for medical professionals (Nesse et al., 2010), we argue that medicine provides a powerful context for teaching evolution that should be more prominent in biology classrooms.

○ Evolutionary Medicine Offers Many Examples of How Evolution Helps Us Understand Disease

The range of evolutionary applications to medicine expands far beyond commonly used classroom examples such as antibiotic resistance, providing a rich pool of relevant, but currently underused, examples to implement in classrooms. Evolution is transforming our understanding of cancer (Greaves & Maley, 2012), including the discovery that lowering the dosage of chemotherapy can be a more effective treatment strategy (Gatenby et al., 2009). Carrying the apolipoprotein E4 allele is a major risk factor for developing Alzheimer's disease in industrialized populations, but

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in a hunter-forager population with a high parasite load, this allele actually slows cognitive decline (Trumble et al., 2016). Researchers have debated for years whether tuberculosis in New World populations reached these populations upon the arrival of Columbus or through some mechanism independent of European colonialists. However, analysis of DNA from lesions in ancient skeletons in Peru suggest that cases of TB in the New World were transmitted from seals (Bos et al., 2014). These examples, alongside others in evolutionary medicine, offer a captivating context for students to learn and apply evolutionary principles. They illustrate the relevance of evolutionary tools and lenses to medicine and provide a more comprehensive understanding of human disease.

Teaching evolution through medical examples also provides opportunities to reinforce students' understanding of the nature of science. Teaching the nature of science is an important antecedent to promoting evolutionary understanding and acceptance (Dunk et al., 2017; Scharmann, 2018; Nelson et al., 2019). Teaching the nature of science helps reduce perceived conflict for students who view evolution, and human evolution in particular, as controversial (Scharmann et al., 2005; Barnes & Brownell, 2017). Because the types of questions central to evolutionary medicine rarely have simple answers and require a consideration of all possible hypotheses, evolutionary medicine further amplifies the importance of the nature of science. For example, asking students to hypothesize why we are susceptible to nearsightedness can generate many possible hypotheses. Indeed, the complexities of disease etiology, human biological and cultural variation, and the intricacies of evolutionary processes lead to numerous plausible hypotheses that are often difficult to test. Teaching evolution through medical examples provides many opportunities for students to learn that science is about uncertainty, and that their responsibility as scientists is to systematically test and evaluate how the world works.

○ EvMedEd – A Resource to Help Integrate More Medical Examples

Instructors who want to integrate medical examples into their evolution courses and units of study may not know where to begin. Existing resources for learning about and teaching evolutionary medicine are extensive but decentralized. They include case studies (e.g., National Center for Case Study Teaching in Science, http://sciencecases.lib.buffalo.edu/cs), curricula for high school students (e.g., Beardsley et al., 2011), online videos and podcasts, textbooks, and journal articles. However, for an instructor unfamiliar with this landscape, finding appropriate materials or accurate information may be daunting. To help instructors integrate more medical examples into their evolution curriculum, we have created an online resource called EvMedEd that provides online educational resources in evolutionary medicine.

EvMedEd is a free, online, open-access resource for evolution and medicine education. It is sponsored by the International Society of Evolution, Medicine, and Public Health and the Arizona State University Center for Evolution and Medicine. EvMedEd provides links to over 1600 online resources curated for quality by evolutionary medicine experts, including online videos, websites, books, journal articles, and podcasts.

EvMedEd also provides teaching materials for instructors, including teaching modules that can be included in classrooms, course syllabi with reading lists, PowerPoint slides, assignments, and assessment materials for measuring student understanding of core concepts in evolutionary medicine. These resources have been developed with best practices in mind, and many are student-centered activities. Links to peer-reviewed articles about how to improve teaching in evolutionary medicine (e.g., core concepts in evolutionary medicine or approaching evolutionary medicine from an interdisciplinary perspective) are also included and more will be added as they become available.

EvMedEd is also home to a growing catalog of medically relevant examples (MREs) of evolution, including overviews of completed or ongoing research studies, current debates in evolutionary medicine, and case studies that illustrate applications of evolution to medicine. Each MRE includes a brief background, an elaboration on which core principles it exemplifies, and links to articles, videos, and classroom materials relevant to that example. MREs are searchable by

Figure 1. Example page from EvMedEd's catalog of medically relevant examples.

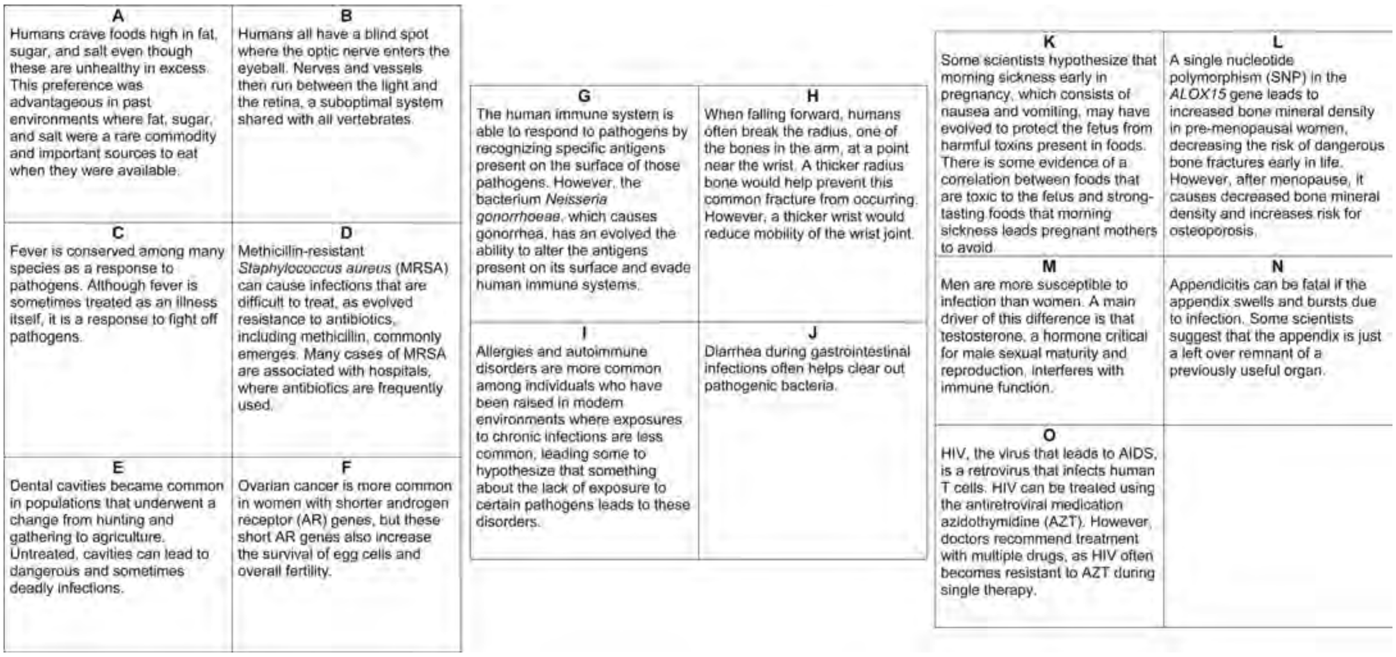

Figure 2. Cards used in an evolutionary medicine card-sorting activity available on EvMedEd.

both the principles they exemplify (e.g., trade-offs, phylogeny) and the topics they touch on (e.g., infectious disease, mental health). This allows instructors to find examples and resources based on the need to teach specific evolutionary principles or medical topics. One MRE is the story of Myxoma viruses and rabbits in Australia (Figure 1), where a virus was released in an attempt to control a growing population of invasive rabbits. While the effort was successful at first, the virus eventually stopped killing rabbits. Not only did rabbit populations evolve resistance, but the virus populations evolved to be less virulent over time. This exemplar provides a means to teach host–pathogen coevolution and trade-offs between virulence and transmission, while also offering an opportunity for students to improve their ability to design experiments, which is well established as challenging for students (Brownell et al., 2013; Dasgupta et al., 2014).

An example of an evidence-based teaching activity available on EvMedEd is a card-sorting activity designed to introduce evolutionary medicine and six main reasons for why bodies remain vulnerable to disease despite the action of natural selection. This activity is designed for use in introductory biology classrooms with students who already have a basic understanding of evolution. Students are given cards, each of which contains a statement with a suggested evolutionary explanation for a human vulnerability for a specific ailment or disease (Figure 2). When invited to sort the cards into categories, students tend to focus initially on surface features, such as the kind of disease. They are then presented six main evolutionary explanations for vulnerability to disease:

(1) Mismatch between aspects of human bodies and novel environments

(2) Pathogens that evolve faster than humans do

(3) Constraints on what natural selection can do

(4) Trade-offs that keep any trait from being truly “perfect”

(5) Traits that increase reproduction at the cost of health

(6) Protective defenses, such as pain and fever

After exposure to this framework, students get a chance to use it as they sort the cards again.

○ A Call for Contributors

EvMedEd is intended to be a grassroots effort and welcomes your contributions. Descriptions of teaching modules, innovative class activities, and course syllabi are all welcome. We expect that EvMedEd will develop over time as more resources are added and as new advances in evolutionary medicine shape the field. For more information, please visit the website at EvMedEd.org.

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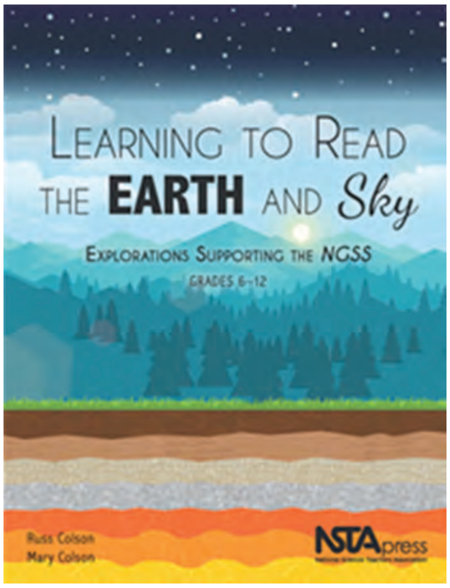
BOOK REVIEWS

AMANDA GLAZE-CRAMPES, DEPARTMENT EDITOR



SUPPORTING NGSS WITH AUTHENTIC SCIENCE EXPERIENCES

Learning to Read the Earth and Sky: Explorations Supporting the NGSS, Grades 6–12. By Russ Colson and Mary Colson. 2017. NSTA Press. (ISBN: 9781941316238). 426 pp. Paperback, $39.95.

When Russ and Mary Colson's inspirational book first arrived in my hands, dear reader, I did not know what to do with it. I had been teaching earth and space science to high schoolers for a few years, and I was proud that I had learned my way around some of the content. But *Learning to Read the Earth and Sky* is a master class, and I needed a few more years of learning before I was ready to leverage its powerful lessons in my classroom. Now, however, I'm gratefully using what it's taught me to transform all my science courses.

Mary is a middle school teacher and Russ a collegiate instructor; together, they've written a tremendous resource that provides ideas and techniques, broadly defined, for using the *Next Generation Science Standards* (NGSS) as a platform for practicing real science with students. This is not a handbook, however, or a curriculum. Instead, the Colsons interweave simple but evocative examples of "teacher moves" with thoughtful stories and quotes from scientists and educators alike. The layout, rich with illustrations, sample student work, and callouts, is a powerful complement to the encouraging and detail-oriented text.

One of the biggest concerns for teachers who want their students to engage in more authentic science practices is that their classes will accidentally descend into chaos and pandemonium. To alleviate that concern, the Colsons have structured much of this book around frameworks they call Example Activity Designs. Each is based on a specific science practice, including iteratively making observations, asking questions, and graphing. I was particularly impressed with their recommendations for transforming a well-tested procedural exercise into one where students build controlled experiments; this technique, which I first learned from the AP Biology teaching community, is beautifully explained here.

There is an abundance of rich pedagogical content knowledge to be found within *Learning to Read the Earth and Sky*. My favorite, one that also drives my classroom, is the idea that teacher and students are colleagues and fellow scholars. I co-teach the most introductory inclusion science class at my high school with a special education teacher, and we find ourselves constantly working to rewrite the narrative that certain students don't have expertise or hold knowledge about their world. I also appreciate how the Colsons give the reader permission to intentionally focus their instruction. Teaching and learning a year's worth of science content shouldn't feel like a forced march; instead, teachers must find ways both to break big concepts into smaller pieces and to prioritize scientific experiences with some – not all – of the component ideas.

This may not be the very first book to reach for if you are new to science teaching. However, if you are looking for a breath of fresh air, new ideas, and unwavering support in helping students authentically practice the doing of science, I recommend this book without reservation.

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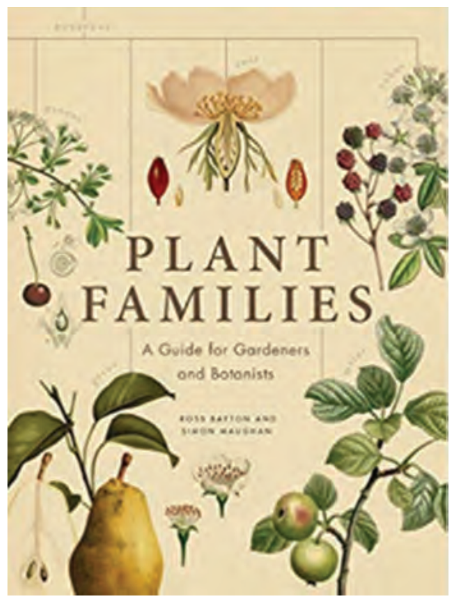

BOTANY

Plant Families: A Guide for Gardeners and Botanists. By Ross Bayton and Simon Maughan. 2017. University of Chicago Press. (ISBN: 9780226523088). 224 pp. Hardcover, $25.

Even before opening the covers, any science book lover will appreciate the appeal and quality of *Plant Families*. Great attention has been paid

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to the details of presentation; in particular, the volume unites art with science throughout. Each page is carefully laid out with text and elegant historical illustrations depicting the topic under discussion. Drawings of details and line diagrams are frequently used to more clearly examine details of structure and process.

As is to be expected for a guide book, *Plant Families* is beautifully organized. The introduction provides brief discussions of the current plant families, representing plant evolutionary trends from the earliest mosses and liverworts to the more complex and later-evolved angiosperms. Similarly, the explanation of the distinction between monocots and eudicots helps the reader understand the differences between these two major plant groupings. The introduction also provides a very helpful overview of what to look for when identifying plants, including growth cycle, location, anatomical features such as leaf placement and shape, flower type, and characteristics of fruits and seeds. Lastly, an extensive dichotomous key walks the reader through the process of identifying the family of a plant sample. Following this is the true focus of the book: presentation of the plant families themselves. Two to four pages for each family provide information about size, range, origin, flowers, fruits, leaves, and uses. The authors make note of invasive species and the care gardeners must take in planting decisions to limit their spread.

Although written with gardeners in mind (the "Uses for This Family" sections primarily give tips for purchase and planting in different types of gardens) there are many aspects of this little volume to interest the biology teacher and student. The introduction's dichotomous key could easily be the basis of a fun and informative plant identification activity. The worldwide scope of this guide makes it a fascinating overview of plants and plant adaptations, although this also makes it less useful in specific North American plant identifications. Scattered throughout are gems of biological information – for example, the flowering spadix of the arum family sometimes heats up to spread pollinator-attracting odors more widely. Different water absorption adaptations among the bromeliads include roots in pineapples and desert bromeliads, water-absorbing leaf scales in air plants, and water-collecting urns in rainforest epiphytes. Legumes and their symbiotic bacteria are critical in nitrogen fixation. Fig receptacles have tiny internal flowers that are fertilized by a specific female wasp. The dried firm wall of *Luffa cylindrica*, a member of the cucumber family, is the source of the loofah sponge. Oak and beech trees produce intermittent bumper crops of nuts called "mast," designed to overwhelm seed predators and ensure that some seeds survive to germination. These and many other fascinating tidbits of information await the *Plant Families* reader.

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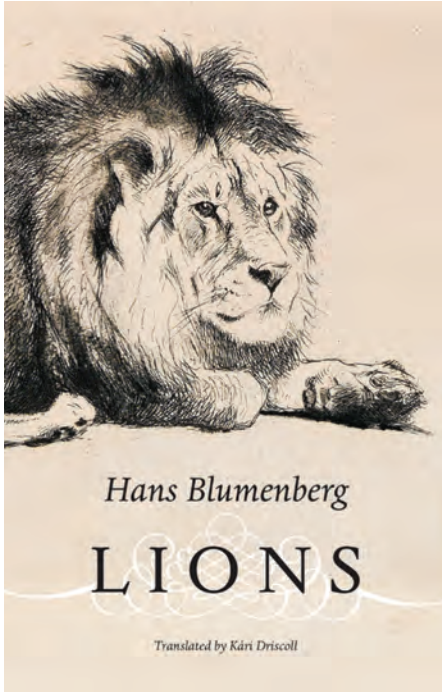
THINGS AREN'T ALWAYS AS THEY SEEM

Lions. By Hans Blumenberg. 2019. Seagull Books. (ISBN: 9780857424303). 104 pp. Hardcover, $27.50.

French fabulist Jean de La Fontaine wrote about an artist who painted a lion that had been killed by a hunter. In his story, people praise the painting because it shows human superiority over animals. A lion, overhearing the opinions of the people, chalks up their idea to imagination, explaining that "with better logic, we'd be winners in this fight if my fellow lions could paint or draw." Viewing the painting *The Persecution of Christians under Nero*, a little girl burst into tears because



she observed that a lion in the corner didn't have a Christian. To her, if Christians were on the lions' menu, there should have been enough for everyone. Fiesco, Count of Lavagna, created an animal fable on the political history of Genoa. When a bulldog tried to seize the throne, other animals, including the lion, revolted and eventually the lion was crowned king. Other stories in this book include such themes as sea lions, the baptized lion, and the story of Buddha changing himself into a lion.

Written not by a scientist but by the late, distinguished German philosopher Hans Blumenberg, the book uses lions as metaphors for the relationships between humans and animals. Thirty-two unique stories of two to nine pages each, including many philosophical analyses, make up this unusual volume. Originating in global locales from Abyssinia to Zurich, the stories are a mixture of fables and facts, old and recent, simple and complex. Besides the author, other philosophers such as Schopenhauer, Plato, Kant, Socrates, Nietzsche, and Bertrand Russell make appearances in these pages, along with historical figures such as Rousseau, Euripides, Luther, Goethe, Dostoevsky, Picasso, Aesop, Boswell, Ibsen, Hitler, Kaiser Wilhelm, the prophet Isaiah, and the apostle Paul, to name a few.

The stories touch on a large variety of subjects, including cannibalism, the power to exist, hunting, religion, politics, homeopathy, and analyses of lions in art, drama, and poetry, along with more philosophical topics such as morality, cosmology, mythology, philology, theodicy, theology, ethology, and metaphysics. The final story is the longest and relates an interesting Thomas Mann tale in which a little boy, Tonio Kröger, fears a pair of lion sculptures that hug the steps of a hotel.

Lions is a short but intense book, written in German and translated into English. For those with a serious interest in philosophy, there are fascinating and detailed discussions in these leonine stories. A clear understanding of philosophy is almost a prerequisite for reading and understanding the book, so it probably will not be attractive to most biology students. A few of the stories are fun to read and more likely to be appreciated by students or instructors who have at least some grasp of philosophy. Some understanding of Latin and Greek will also be helpful, as phrases and sayings in those languages are found in some of the stories. Despite the profound writing, there are occasional touches of mild humor ("Teacher: Name 4 animals in Africa; Pupils: 3 lions and a rhinoceros"). At the end, 18 pages of detailed supporting notes provide sources and additional background that can help readers get the most out of the 32 vignettes. Perhaps the best opinion is this old maxim shared by the author: "Philosophy is too hard for human beings."

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CLASSROOM TOOLS & MEDIA REVIEWS

JEFFREY D. SACK, DEPARTMENT EDITOR

Learn.Genetics: DNA Extraction (Genetic Science Learning Center, https://learngendev.azurewebsites.net/content/labs/extraction/)

With shrinking classroom budgets and stricter regulations about what science teachers can and cannot do in their classrooms, there is a strong need for more virtual opportunities for students. Virtual or online laboratory activities are not only usually free, but they offer students experiences they might not be able to have in the real world. There are many places on the Internet where students can go to learn biology and practice their laboratory skills. One such site, called "Learn. Genetics" (https://learngendev.azurewebsites.net/), has a large collection of these activities that are user-friendly and suitable for students of all ages.

Among the virtual labs on the Learn. Genetics site is one in which students can participate in a DNA extraction (https://learngendev.azurewebsites.net/content/labs/extraction/). Removing DNA from human cheek cells may be prohibited in public school classrooms due to safety concerns, but here students can do it virtually. Students work their way around a lab, moving through each step of the extraction. They virtually use chemicals, pipettes, and centrifuges to pull the DNA from the cheek cells and then isolate the material in a test tube. The only computer requirements for performing the simulation are an Internet connection and a web browser with the Flash extension.

When first launching the simulation, the user is presented with a question as to why it would be beneficial to extract DNA from an organism. The simulation provides some uses of extracted DNA and then describes the materials needed for the actual extraction. It then explains what DNA is, where it is found within a cell, and how it forms chromosomes. The simulation goes on to describe the procedure the user will follow. These steps include collecting cheek cells, bursting the cells to release their DNA, separating the DNA from proteins and other debris, and isolating the concentrated DNA.

Students start by clicking on a buccal swab and moving into the subject's mouth. The animation automatically scrapes the cheek cells and moves the swab into a microtube for centrifugation. The pipette is then used to add lysis solution to the tube before the tube is placed in a water bath. The simulation provides a close-up view of the cells bursting open and releasing their genetic material. From here, students use the pipette to add salt to the DNA solution in order to cause proteins to clump together. The tube is then placed in a centrifuge to separate the clumped proteins from the DNA (the proteins sink to the bottom). Alcohol is used to force the DNA out of solution and to make it visible.

There is no replacement for real-life, hands-on learning. Research has shown that when students actually *do* science instead of just reading or hearing about it, they tend to retain a lot more of the information. However, when supplies are limited or safety concerns arise, doing a virtual simulation is the next best thing. The DNA extraction simulation on the Learn.Genetics site is an excellent activity that is appropriate for students in middle school and up. The entire virtual extraction is animated with high-quality graphics and is highly interactive. There is only limited text for students to read, so English-language learners will have no trouble being fully engaged in the activity. Teachers may want to use this DNA extraction as a pre-lab activity to prepare students for actually pulling DNA out of a real organism. There is also a link with detailed instructions on how to extract DNA from just about anything; teachers may wish to follow these if they decide to perform the extraction in their classrooms.

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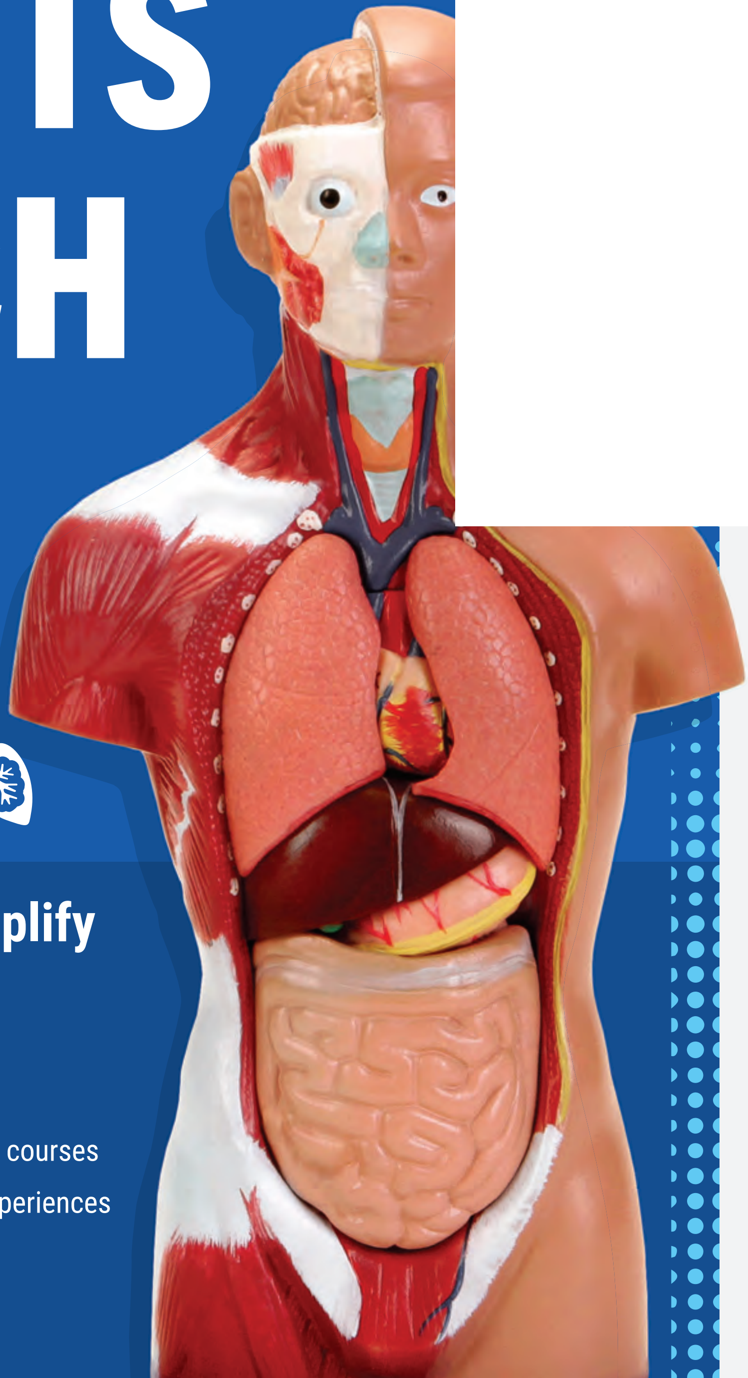
Index to Advertisers

The February BioMystery Answer

These long-extinct marine arthropods are eurypterids, or "sea scorpions," distantly related to modern animals such as the arachnids. There are 250 known species, most of which lived during the Silurian Period. They died out about 250 million years ago, around the time of the Permian-Triassic extinction event. The largest were >2 m in length and the smallest <20 cm. Their name means "broad wing," after the paddles they used for swimming. This is a photo of *Eurypterus remipes* from Herkimer County, New York. In 1984, this species was named the state fossil of New York, but examples are found in strata worldwide. (Photo taken in the Tokyo Natural Science and History Museum by W. F. McComas).

IT TAKES GUTS TO TEACH A&P



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